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[*Continued on page (III) of Cover.*

GENERAL DISCUSSION ON "ELECTRICAL ENGINEERING EDUCATION"

(*Before* THE INSTITUTION *16th December and before the* NORTH-EASTERN CENTRE *22nd November*, 1937, *also before the* NORTH-WESTERN CENTRE *4th January, before the* NORTH MIDLAND CENTRE *18th January, and before the* SOUTH MIDLAND CENTRE *7th March*, 1938.)

INTRODUCTORY REMARKS OF Professor C. L. FORTESCUE, O.B.E., M.A., Member.

(1) Scope of the remarks.

My remarks are intentionally restricted to the training of those who may be expected to qualify for Corporate Membership of The Institution; from the time of their passing the School Certificate Examination (or its equivalent) to the time at which they start upon their experience in a responsible position as an electrical engineer which is required as a qualification for Associate Membership. This period includes both the theoretical and the practical training of the young electrical engineer from the age of about 16 to the age of 23 or 24 years.

(2) The objectives of the training.

Before attempting to decide upon the best use that can be made of this period of the young man's life, it is necessary to be quite clear as to what is required of him at the end of the period. The desirable qualities for a young engineer are twofold:—

(*a*) A knowledge of the practice of that branch of electrical engineering in which he is about to take responsibility; also a sufficient knowledge of modern languages to enable him to read the literature of his subject, and enough grounding in science and mathematics to enable him, in due course, to take his own part in its advancement.

(*b*) The personal qualities of quick perception, good address, initiative, tact, and that purposeful honesty which commands the trust and willing co-operation of those with whom he is working.

The personal qualities are almost wholly natural, inborn characteristics admitting of only a limited development during the period of the young man's life now under discussion. They are, nevertheless, all-important, and the problem of the educationalist is to devise a course of theoretical and practical training which, whilst giving the young engineer the experience and the data necessary for dealing with his problems, shall at the same time develop the personal qualities to the greatest extent.

In attempting to solve this problem the educationalist finds himself in a position utterly abhorrent to an engineer; for he has neither control over his raw material nor the means of measuring the results of his efforts!

(3) The general lines of the required training.

Certain generalizations are, however, possible. The majority of the boys who ultimately become Corporate Members of The Institution come from secondary schools, and the advantage to a boy of spending 1 or even 2 years at school after the School Certificate stage can hardly be gainsaid. At the other end of his training: since the young man is about to undertake some degree of responsibility in which lack of success is likely to be disastrous for his whole career, it is obvious that at least the last year should be devoted to the particular branch of the electrical profession which he is about to enter. For the rest of the available time, widely varying systems of training have grown up, all of which have produced successful men, and any one of which may be advocated as the ideal on the grounds that it has produced this or that successful individual. The educationalist has, however, to avoid drawing any conclusions from outstanding success or outstanding failure, and to rely on his observations of a large number of students and of the work they are called upon to perform in after life.

(4) The university plus postgraduate apprenticeship *versus* works and technical institutions.

Each of these schemes provides adequate training, and the two are becoming more and more alike. The university course is still the more expensive to the individual and to the community. Is this extra cost justified? The answer to this question is important, because the continuance of university courses of training in engineering and other branches of applied science—not excluding even the biological sciences—is dependent upon it.

The most important influence of the university training arises from the longer time available and from the fact that the students can devote the whole of their time and energy to the work in hand. This leads to the university courses being generally more philosophic and fundamental in outlook and enables the students to stand aside, as it were, and take a view of their problems with all the features in their proper perspective, and then—perhaps most important of all—to plan experiments to test the accuracy of their conclusions or to ascertain essential facts or data upon which conclusions can be based. This develops a tendency to search for fundamental reasons and a healthy dissatisfaction with merely accepting the facts of a given state of affairs without logical support. Most engineering graduates agree that although the stress of practical commercial conditions may often render it imperative to make decisions without logical investigation, the fact that they have acquired both the inclination to base decisions on scientific argument and the knowledge enabling them to do so, constitutes a great part of their professional qualifications.

This attitude of mind is, of course, by no means confined to the university graduate. The technical institutions are following the universities as nearly as the available time permits, and even practical works experience contributes. But at present neither is equal to the university in this respect.

The sandwich systems provide, in reality, little that the works plus part-time study at a technical institute cannot provide, and the lack of continuity of both the theoretical and the practical training is a serious disadvantage.

(5) The theoretical training.

This is complementary to practical training and must always consist of those parts of the engineer's training which cannot easily be obtained in the course of practical work. The subject matter is substantially the same whether taken before or after works experience, or concurrently with it. A complete scheme which, in my opinion, is a near approach to the ideal for an electrical engineer is given in Appendix 1.

In considering this scheme it has always to be remembered that the knowledge it is possible to acquire during the training period is only a part—and quite a small part—of the knowledge an engineer will eventually find necessary for his professional work. Any scheme of training must therefore be a matter of picking from a wide field those parts serving the double purpose of encouraging intellectual development and, at the same time, providing a knowledge of the principles and methods which will be required by the young engineer in order that he should be able to cope with his practical problems as they arise. A wide choice is obviously possible, and the scheme outlined in Appendix 1 provides for a considerable choice, depending upon the immediate interests of the student and the teacher. Present-day practice plays a secondary part in this scheme, and, as it is intended for electrical engineers, the practice of the mechanical engineer is wholly omitted. (This, however, does not mean that the electrical engineer need not acquire a considerable knowledge of theoretical applied mechanics.) Design problems also play a minor part—only sufficient to bring to the students' notice the general nature of the way in which the best compromise between antagonistic requirements can be reached. Both current engineering practice and practical design are matters which the young engineer should study on his own initiative in the course of his practical experience. Laboratory work plays a large part in the scheme outlined in Appendix 1, but as a means of developing a scientific outlook and powers of observation rather than as a course of training in practical works testing.

(6) The practical training.

A schedule of practical training is set out in Appendix 2; the portion relevant to the present discussion being paragraph (B). It will be noted that little stress is laid on the acquisition of manual skill. It is an accomplishment giving pleasure to a genuine engineer similar to that of athletic attainment. Both are to be encouraged, but neither is essential to a training scheme. For those about to take executive positions in the electrical industry it is far more important to have a knowledge of such matters as the factors influencing production and costs; the effects of the conditions of working such as heating, lighting, and ventilation; and the trade-union organizations and their activities.

The schedule of work set out may often involve keeping postgraduate apprentices in the works outside normal working hours. This, however, is quite natural for young men training for executive posts, and an occasional long week-end is a full compensation! There is, in fact, much to be said for giving the postgraduate apprentice some flexibility in the matter of timekeeping. Works managers need have no fear that it will be abused if the work given to the apprentices is of real value and has, possibly, some small element of responsibility.

The relation between the last year of this practical training (the second or third, depending upon circumstances) and the branch which the young engineer is entering is a matter of greater importance than is usually supposed. The apprentice cannot become an efficient assistant until he has had the opportunity of studying intensively the methods adopted and the conditions prevailing in the branch to which he is going. If he is to do anything more than routine technical work, a whole year is not too long. This may sound impractical and unworkable, and it may be objected that few young engineers know so long beforehand just what opportunities will be offered to them when they are out of their apprenticeship. But I would submit that it is at least as important that the management of our engineering organizations should plan for the future in respect of personnel as it is in respect of materials. The habit of assuming that when a vacancy occurs here or there, someone will be found who can be put in, is an unsatisfactory policy which, unfortunately, is only too prevalent.

(7) Research.

For those university students having the necessary gifts, one year of research in physics or engineering is at least equivalent to a year of apprenticeship in works, and should be accepted as such.

Appendix 1.—A scheme of theoretical training for electrical engineers.

(A) *School Certificate stage, ending at the age of about 16 years.*—Though not part of the engineering training, it is desirable to include this stage since it is the basis of the subsequent work. It should consist of: (i) English, general history, and geography. (ii) A modern language—firstly spoken, then read. (iii) A blend of mathematics and mechanics, not heavily stressing pure mathematics. (iv) Physics and chemistry taught as a single subject in which practical accomplishment simply described takes precedence over basic theory.* (v) Some aspects of biological science or of geology; for example, the study of some of Huxley's essays, somewhat as in the old days such books as Boswell's "Life of Johnson" were read under the impression that good English was cultivated thereby. (vi) Freehand and perspective drawing; handwriting.

(B) *Higher Certificate stage,* 16 *to* 18 *years of age (for boys staying* 2 *additional years at school; boys going straight*

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* There is no serious difficulty in devising a course of this kind which is both logical and interesting and which is at the same time by no means a "soft option." General physical principles must be insisted upon, but subtle arguments should be left to a later stage. For example, elementary electricity should be taught by the water analogy and not by attempting to prove the inverse square law.

into works miss much of this).—(i) Modern history and economic geography, with an introduction to the principles of economics and their application to modern industry. (ii) A modern language. (iii) Mathematics and mechanics, tending more in the direction of pure mathematics than during the School Certificate stage. (iv) Physics and chemistry, taken together and still without too much of the philosophical aspects.[*] (v) The use of hand tools in some form or other—anything interesting that calls for manual skill. (vi) Drawing—both freehand and engineering.

(C) *First engineering stage* (*first year at the university for boys entering directly from school; first- and second-year part-time study for those passing directly to works from school*).—(i) Mathematics and mechanics. (ii) The properties and uses of structural materials. (iii) Applied heat.[†] (iv) Applied electricity.[†] (v) Chemistry.

(D) *Second engineering stage* (*second year at the university; second and third year for part-time students*).—(i) Mathematics and mechanics. (ii) The theoretical aspects of the use of engineering materials. (iii) Applied heat; prime movers.[‡] (iv) Applied electricity, more advanced. (v) General physics.[§]

(E) *Third electrical engineering stage* (*third year at the university; fourth and fifth years for part-time students*).—(i) Theoretical electricity (advanced).[||] (ii) Methods of electrical measurement. (iii) Industrial economics in its engineering aspects, *or* advanced mathematics with a bias towards engineering applications, for students who have shown themselves to be possessed of the necessary aptitude for the subject. (iv) A critical and scientific treatment of *one* aspect of electrical engineering, such as electrical machines, electrical power transmission and distribution, telecommunications (audio-frequency), telecommunications (radio-frequency).

(F) *Laboratory work.*—Experimental laboratory work, designed to illustrate laws and principles and to encourage observation and inquiry, is an essential part of any training of this kind. The experimental work must be kept approximately in step with the teaching, especially in the early stages.

The time devoted to laboratory work should be about equal to the time devoted to lectures and tutorial work combined. All awards at the end of the successive stages, and the degree, diploma, or certificate conferred at the end of the course, should be made to depend in considerable part on the manner in which this laboratory work is performed.

Appendix 2.—A scheme of practical training for electrical engineers.

The conditions vary so widely that the scheme can only be expressed in very general terms.

(A) *Four- to five-year period for boys entering the works from school.*—(*a*) First 2 or 2½ years: machine-shop and bench operations, as for a trade apprentice. At the end of this period it should be possible, with the assistance of reports from the technical school, to pick out those apprentices who may be expected to enter the higher grades of the profession. (*b*) Second 2 or 2½ years: promising apprentices should follow the scheme set out for the postgraduate apprentices under paragraph (B) below. The remainder, who may expect to become expert mechanics, draughtsmen, and routine technical workers, would spend most of this second period in works and drawing office.

(B) *Two-year period for post graduate apprenticeship.*—(i) Machine shop: partly carrying out the actual operations but principally recording and reporting on the performance of the machines, the results of inspection of the product, and the cost in time and money of the various operations. (ii) Pattern-shop and foundry: recording the time and cost of the operations; and examining critically the economics of the various practices in the foundry. (iii) A limited time in the testing and inspection department [partly in conjunction with (i) above]. (iv) The last year should be devoted to the particular branch to which the young engineer is going on completion of his apprenticeship. This period should include experience in the designing office, the time being spent on genuine designing work under the direct supervision of a more senior member of the staff.

INTRODUCTORY REMARKS OF Colonel H. CECIL FRASER, D.S.O., O.B.E., T.D., Member.

Those who are concerned to-day with the education of the future electrical engineer have two distinct duties to perform. The first and most important of these is to the community in general, to whom they owe it to produce a valuable and efficient public servant, and a good citizen; the second is to the student himself, who must be provided with an education which will, as far as possible, ensure his success in his chosen career. At the present time, when the ability of her electrical engineers becomes ever more vital to the welfare of our country, it is worth inquiring with what success these duties are being carried out.

At the outset, it is necessary to distinguish between education and the mere acquisition of information. The process of education involves bringing all the latent physical and mental possibilities of the raw material to the best and fullest fruition possible under the circumstances. It is, in short, the making of the man—a very different thing from filling his head with a variety of information. This is not to suggest that he will not require information—much of it being, under modern conditions, extremely complex information—in order to know his job and carry it out effectively. But such technical knowledge must be in the nature of a top-dressing; it cannot take the place of the subsoil. Unless a man has received a sound education on general lines, he will be unable to digest the information he derives from his textbooks. He will fail to set his technical equipment in its proper relation to his life as a whole; he will not be fitted to take broad views and discern underlying tendencies; and he will, in consequence, be ill-suited to fill those positions of high trust and responsibility which electrical engineering holds out to-day to those who are capable of filling them.

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[*] See footnote on page 162, col. 2.

[†] Even at this stage the treatment of both heat and electricity should relate only to the simpler aspects of the theory.

[‡] This stage will include a reasonably complete treatment of theoretical thermodynamics.

[§] This would include physical chemistry, an outline of modern views of atomic and molecular structure, and such branches of optics and sound as can reasonably be dealt with in the time available.

[||] This course would include the basic theory of the electric and magnetic fields; thus knitting together the simple laws used in the earlier stages.

Clearly, then, if there is to be no lack in the future of men fitted to succeed the great figures of the past and present in electrical engineering, the education of the would-be engineer is a matter of grave concern to the profession. There is a tendency at the present time to regard the acquisition of diplomas and degrees, the painstaking assimilation at an early age of a set of arbitrarily—and sometimes, perhaps, unwisely—chosen facts, as proof that a candidate is likely to develop the energetic initiative, the wide knowledge of men and things, that are required of the successful electrical engineer. By the candidates themselves such academic qualifications are regarded as an indispensable passport to the pay-roll of electrical engineering firms. Hence the School Certificate and the Bachelor of Science degree are becoming more and more, not useful servants, but tyrannical masters. Time and effort are spent upon them which might more properly be diverted into other channels, and both employer and student are the sufferers.

If, however, the education of candidates for engineering posts at present leaves something to be desired, it is necessary to consider the particular qualities which it is desirable to develop in such candidates, and to suggest briefly the lines along which they may be fostered. The engineer must, I think, reach a high standard in three separate respects if he is to succeed in his profession. First, and most important, he must possess the correct temperament for his job. He must understand both how to obey and to be obeyed; how to face strain and sometimes danger; and how to stick to his guns in the face of difficulties, opposition, and disappointment. Secondly, he must be adaptable. He must be endowed with that versatility of mind which will enable him to grasp rapidly a fresh problem or a new set of circumstances, and make swift and sound decisions at short notice on data which will generally be inadequate. Thirdly, he must be physically fit. He will be called upon, in the course of his everyday activity, to stand up to conditions of unceasing strain and concentration, whether in control of plant, in the field, or at the office desk. Under such conditions the weak link, the faulty turnbuckle, must sooner or later inevitably part, and the delinquent may endanger not only his own career but the comfort, the property, sometimes, indeed, the life, of others.

I wish now briefly to consider these three qualities which are so essential to the successful engineer, and to outline the educational principles most likely to lead to their acquisition and development. First, in regard to physical fitness; there are encouraging signs that we are awaking to the need of maintaining the nation in a sound and healthy condition. Much is being done, both officially and voluntarily, to promote this end. Excellent facilities are provided in most modern secondary schools. Yet there remains in the life of the average young man an important period during which his bodily health is ill cared-for. This is the period during which he is studying at a university or training college in preparation for his chosen career. It is a matter for grave doubt whether facilities for games and physical training at most provincial universities are in any way adequate, or whether students make the best use of those which exist. In part this is due to the prevalent lack of means and space for expansion, in part to the conception of the university—in particular, the provincial university—as an institution from which, by paying the stated fees, a student may emerge at the end of a stated period in possession of the appropriate degree. Nothing could be more harmful to the quality of the recruits to the great professions, or more prejudicial to the value of the universities. The majority of candidates for engineering posts at the present time are drawn from the provincial universities. It is up to employers to insist that, during the year or years that they spend there, their general education is continued and expanded. No part of this education is of more importance in the long run than the physical, and it must be the constant endeavour of the universities to improve their facilities in this respect. Mental ability, however essential to the prospective electrical engineer, is not the only requirement of his profession; physical fitness is equally indispensable.

A far more debatable question than this is the cultivation of the other two qualities I mentioned in discussing the requirements of success in engineering, and which I called "suitability of temperament" and "adaptability." If it is principally at the universities that improvements are to be looked for in physical education, it is in the secondary schools and in the homes of this country that the foundations of character and temperament must be laid. True of the majority of great professions, it is eminently true of electrical engineering that there is need for an unlimited supply of men endowed with readiness to assume responsibility, the power of handling men, and the adaptability which enables them to face rapidly-changing situations with skill and confidence. These are qualities of which the rudiments must be implanted at an early age, or they are likely never to be implanted at all. To-day, a variety of educational theories are current, many of them misguided or fantastic: but the essence of the problem has never been more clearly understood than it was during the great period of expansion in the public schools in the last half of the nineteenth century. Many things have changed since the days of Arnold of Rugby, but his educational principles remain sound and true. The delegation of responsibility to the boys themselves, combined with an ungrudging trust in them, and a wise, unobtrusive, and indirect guidance from above, are the foundations of the most successful educational system ever devised. In boarding schools these principles are perhaps easy and obvious to maintain. It is in the secondary schools that the truth that success in examinations is no substitute for success in the general rough-and-tumble of school life requires to be more widely understood. A year's service as prefect or monitor can be of vastly greater educative value than many certificates, and success or failure in such positions a far more certain indication of capacity from the point of view of the employer. It is only fair that such qualifications should be recognized, and allowed in certain cases to compensate for academic and technical deficiencies. Technical knowledge sufficient for all practical purposes can be swiftly acquired in later life by an average brain, while early failure in examinations is often due to unwillingness to work at uncongenial and apparently irrelevant subjects. But the foundations of character must be early laid, and constitute a much more worthy object for the schools of this country than the academic forcing of promising plants, or the soulless cramming of candidates for the School Certificate.

I have been led to speak somewhat generally on the subject of education, and perhaps I have seemed unduly to decry the importance of technical efficiency in electrical engineering. If this is so, it is because there is no danger of its under-estimation to-day. In the many and complex fields of modern engineering the technical expert is assured, now and always, of the eminent position which is his due. But, in the nature of things, potentially great technical brains are but few, and those who possess them may be trusted without undue difficulty to realize their own high promise in engineering. It is the education of the average engineer, beyond whose capacity lie the higher regions of scientific research and technical inquiry, that I have been considering. There is no place in industry for the second-rate technician. We must recognize that few can aspire to the mental capacity required of the modern technical expert. We have passed beyond the days of Aristotle, who claimed as his province the whole field of knowledge, and who professed the laudable ambition, which he very nearly fulfilled, of knowing, on all subjects, everything there was to be known. There is no lack of facilities for the development of the supremely capable engineering brain, wherever it may be found. The problem before us is the training of the average brain, and the average character, of the ordinary recruit to the profession. There is a danger at the present time that industry may pass under the control of what may be termed a "technical bureaucracy." Candidates will be liable, unless we see a trend away from present conditions, to spend the most formative and educationally useful years of their lives in a dull grind to attain the uniform standard of academic efficiency demanded by national certificates and university degrees. Such men will not be those best fitted to carry on and enhance the traditions of the British electrical engineer, and the rectification of a potentially unhealthy state of affairs in education is thus in the interests of all who are connected with the profession.

It is, then, the development of character no less than of mental efficiency that must be the concern of the authorities in whose hands lies the education of the professional classes. The development of mental efficiency is recognized as valuable and is sedulously fostered under present-day conditions. Unless, however, we can find means to combine it with the development of character, there is liable to ensue in electrical engineering a state of competent stagnation rather than one of vigorous enterprise. Much can be done now, but the result depends ultimately on the future, and the future depends on the men who will control the industrial policies of to-morrow. It is incumbent upon all those whose concern, whether as schoolmaster or employer, is with the education of this rising generation, to ask themselves how far the present system is satisfactory and in what respects reform is possible; and to remember, always, that educational systems, like books and drugs, are good servants but the worst possible masters.

INTRODUCTORY REMARKS OF Mr. F. H. CLOUGH, C.B.E., Member.

In addition to such qualities as energy, perseverance, courage, and honesty, which make for success in any walk of life, I think the principal attribute of an engineer is the ability to think in a clear and analytical manner. This enables him to arrange all the physical phenomena entering into a problem in their proper order of importance. In addition, an engineer engaged on creative work should have a lively and scientific imagination, and, to some degree, an artistic sense. In short he should have an "engineering mind."

I think also that an engineer should acquire as much general culture as his other studies and activities will allow, and that he should, in addition to his own language, be able to read, and also speak with reasonable fluency, at least one other modern language.

A young engineer usually has some or all of the attributes enumerated above, and in this discussion we should consider how these can best be stimulated by a suitable system of studies and practical experience. We must also consider how these studies can best equip him for the work he is destined to carry out.

The course of study can be roughly divided into three periods, first cultural, second academic, and third technical. These lead to the Matriculation, Intermediate B.Sc., and Final B.Sc. examinations respectively. The first is taken at school; the second sometimes at school and sometimes at a technical college or a university; the third at a university or at a technical college.

The practical training of the young engineer after leaving school must be associated with his theoretical studies, and we may well discuss the various ways in which practical and theoretical work can be associated. Obviously, a student will benefit more from his practical work if he already knows something of the theory of the work in which he is engaged, and, conversely, his theoretical studies will be more intelligible if he has already had some experience in the handling of the engineering apparatus about which he is learning. Probably a very good arrangement is for the student to enter a manufacturing works or have other equivalent experience after he has attained the standard of the Intermediate B.Sc., but he should have already had the opportunity for laboratory work whilst at the school or college. After this experience he should resume his studies leading to the Final B.Sc., and then take a further course in practical work.

In the works with which I am associated the course followed is not exactly as described above, but the students are divided into two classes. Firstly, there are those who have already taken the B.Sc. degree: these are known as "student apprentices," and are given a 3-year course with deductions for any vacation work they may have already done. Secondly, there is the engineering apprentice, who has not yet taken his degree, and is given a 5-year course. During this period he is given the opportunity of studying for the external London degree at the local technical college.

A large engineering and manufacturing organization has need of many engineers of the highest type in its research laboratories, engineering offices, and other departments. These engineers will be engaged in improving existing designs, evolving new products, and in adapting electrical apparatus to the needs of other industries. Experience in such an organization forms an excellent training for a young engineer, and most companies of this type devote considerable attention to the training of young engineers to ensure that they get the greatest benefit from their apprenticeship.

For many years past the system of training adopted by my own company has been carefully organized. There is an apprentice supervisor with several assistants, and an apprentice committee composed of various senior members of the organization and presided over by the head of the research department. At any one time there are approximately 100 student apprentices, 100 engineering apprentices, and in addition about 200 boys who are receiving a vocational training. The student apprentices are drawn from the various universities and colleges in this country as well as from similar sources in other parts of the Empire and certain foreign countries. The apprentice supervisor, usually accompanied by a member of the apprentice committee, pays periodic visits to a number of colleges and makes a preliminary selection. The candidates then come before a selection committee, who decide whether they should be accepted or not. The engineering apprentices are chosen in a similar manner. The selected students are given a carefully planned course in the various departments of the works, starting in a general department where they receive instructions in general handiwork and the use of tools. Subsequently, they go through a course of training in various other departments, selected according to their own personality and the type of work upon which they will ultimately be engaged. They have, in addition to the actual factory, the opportunity of spending time in the drawing office, engineering department, commercial departments, and research laboratory. Half-hour talks on technical subjects are given by specialist engineers during the winter months, and those students who have already taken a degree can attend a postgraduate course in the local technical college.

It seems necessary that technical studies should be confined principally to fundamental work, for the reason that the amount of technical knowledge now available is so vast that no student can hope to cover even a small portion of it; but as the general fundamental principles are common to most branches of engineering, he should aim at obtaining a thorough grasp of these. It is not possible to do this without some examples illustrating how the principles may be applied, but I suggest that a student should not be taught details, for example, of machine design, except in a very general way. To do this properly would take a long time, and the student would probably find, at the end of his training, that the particular firm who employ him make use of quite different methods.

Great progress has been made in teaching, but tradition still lingers, and there now seems to be no necessity for learning just as a mental exercise; an engineering course is sufficiently bestrewn with natural hazards, without the necessity for making any artificial bunkers. I still remember very distinctly the laborious process I myself went through in order to acquire a certain amount of mathematical knowledge. In the final result, many of the mathematical problems became quite clear and relatively simple, and I grudged the laborious and dark passages I had had to traverse before reaching daylight.

Examinations are another matter which may well be discussed. These have their merits and defects. Their chief merit is, of course, that they give a definite goal to work for, and the examination itself is a test not only of knowledge but of many of the qualities that make for success. On the other hand, working for an examination tends to limit the range of subjects that a student can cover. Much depends on the type of question set by the examiner. In addition to studying the fundamentals of his subject, and their application to various branches of engineering, the student should be shown how and where he can find further information on any subject. Indeed, an examination might well be set where the student was given all the books of reference he might need, as such an examination would represent more closely the condition in which he will be situated in later life.

In conclusion, I hope that the speakers in this discussion will include not only people like myself, whose memory of their student days has become a little obscure, but also the younger engineers who have passed through the student stages more recently and have had the benefit of courses of study and practical experience which are more suited for present-day needs.

ABRIDGED REPORT OF THE DISCUSSION BEFORE THE INSTITUTION 16TH DECEMBER, 1937

Dr. A. P. M. Fleming: The problem of electrical engineering education is twofold: firstly, to ensure the best possible recruits for the industry; and secondly, to use every available means to train and educate them efficiently. Neither of these two requirements is wholly met to-day. The best recruits are not being obtained for industry because those responsible for general education are too remote from it. This situation should be rectified.

With regard to the use of the facilities available for education and training; the university should deal with education from the point of view of the humanities and cultural aspects, and to those students who intend to become engineers the university should impart that knowledge of fundamental and applied science which bears on the practice of engineering. The facilities available for imparting technical instruction are by no means fully used, and industry should undertake a great deal of this responsibility, in addition to the practical training of the young engineer.

Industry is changing rapidly, and for two reasons. One is the rapid and extensive accumulation of new fundamental scientific knowledge, and, arising from that, technical knowledge; the other is the tendency of industry to form combinations of concerns which grow in size. It follows that the large manufacturing organizations of to-day can command large staffs of specialists whose whole duty lies in extending, developing, and improving engineering practice. Their knowledge could be used in assisting in the education and training of the young engineer, and this could be done in two or three alternative ways. One would be for large engineering concerns to undertake some of the technical training which is at present done in the technical colleges, thus releasing time for the more humanitarian studies and for greater attention to fundamentals. This step would be desirable, too, because of the rapid extension of knowledge; it is only those who are engaged in industry whose technical knowledge is up to date. An alternative suggestion would be to arrange for the specialists in industry to teach, at any rate for part of their time, in the technical institutions. In addition to building up these staffs of specialists the large concerns have increasingly developed their facilities for industrial and also fundamental research. No one would deplore more than the progressive industrialist any diminution of the research activities of the teaching staffs of the universities and technical colleges; and industry should not only co-operate with but increase, augment, and assist the furtherance of that activity. Something might also be done to assist in training the future teacher in the technical institutions and universities, so that the intending teacher of engineering should be sufficiently in contact with progressive developments in industry.

The fullest possible account of all the latent possibilities of every recruit to industry, no matter what his social background or his educational level, should be taken and this should particularly apply in a democratic country in a democratic industry. Special attention should be paid to the boy who enters industry from lower educational levels than those referred to in the opening papers.

Dr. F. T. Chapman: In view of the interest aroused by these papers, it seems desirable that the Council should consider the formation of an education group or Section of The Institution for the regular discussion of matters concerned with electrical engineering education. Several sister institutions—The Institution of Mechanical Engineers and The Institute of Marine Engineers, for instance—have such Sections, and they are doing excellent work.

With regard to the relative functions of technical colleges and universities, there appears to be a definite sphere for each type of education, but it is difficult to say exactly where the line of division lies. There is a great deal to be said in favour of the part-time system of education, but it is possibly true to say that there are many entrants into the professions and industry who would come out well-trained whichever course they took.

It is most desirable that the power of taking responsibility should be trained along with the other faculties. The ideal scheme of training would gradually impose an increasing measure of responsibility, starting at a much earlier age than 23 or 24.

Industry in general, and the electrical industry in particular, are taking an increasing interest in education just now, and it is to be hoped that the line which Dr. Fleming has indicated as possible will be carefully considered and possibly adopted by manufacturing firms.

The relative periods of time which should be devoted to training, in works and in college, must vary with the type of position for which the trainee is being prepared. The best scheme of training is one which enables the balance to be changed as the training proceeds, and in accordance with the way in which the trainee himself is developing. The scheme most favourable for the majority of students appears to be one which involves entry to works at the age of 16 or thereabouts, and part-time attendance at a technical college (day as well as evening attendance) for 2 years, followed by 3 years on the sandwich system, half the time in works and half in school; and then, for a few selected young men who have proved their value, one or two years' full-time course in a university. The advantages of this scheme are: firstly, the students approach their theoretical studies in a practical frame of mind; secondly, they come under the influence of part-time teachers, actively engaged in industry.

With regard to the details of the courses; mechanics should be regarded as a branch of physics. Economics should probably be left until the later stages. The trainee will be surrounded by an economic atmosphere during his practical training, and the time for the systematic study of economics and its application to modern industry is when he is mature enough to know something of the electrical industry, to appreciate the importance of the fundamental truths of economics, and to approach the study of the subject in a critical frame of mind.

Dr. C. C. Paterson: The opening papers suggest two main divisions—intellect-training and character-training. It is agreed to-day that what is conventionally called a man's educational period should be devoted to fundamentals and general principles, and that all specialization should be left until later on, when the young engineer has a job. In view, however, of the very wide variety of his duties, it seems quite wrong to imagine that any one method is the only desirable method and principle of education. In the many opportunities which occur of combining the various intellectual traits with the different vocational circumstances, there seems justification for considerable diversity in the university and other curricula. A man who has had a good grounding in physics or chemistry can learn his engineering afterwards; but if he has never learned his physics or chemistry during his regular educational period, he will have difficulty in attaining it afterwards.

Great emphasis should be laid on character, since in industry to-day everything depends on ability to co-operate with other people. The need for Christian principles of knowing how to interact with human nature is met every day.

Prof. E. W. Marchant: The difficulty in the technical education of engineers at the present time is the enormous range of engineering; and it is a matter of observation that students who have passed through courses during the last 30 years have rarely diverged very widely from the branch of engineering in which they started. This leads to the conclusion that in the training of engineers a certain amount of specialization is justified. The scope of electrical engineering to-day is far wider than the scope of the whole of engineering 30–40 years ago, and therefore it is impossible in a college to cover the whole range of engineering in the way that was perhaps possible at that time. It is necessary to specialize if a knowledge of the fundamental principles of modern electrical engineering is to be kept in the forefront of the training. The ideal course of training for engineers is one which includes a day period of training at a college or university, where the student has the great advantage from the educational point of view of broadening his interests by coming into touch with students entering other professions.

In the universities and colleges it is found to be an advantage to provide special work for a student towards the end of his course, instead of taking him through a regular routine with the idea of passing examinations.

Mr. F. Gill: Dr. Fleming has outlined a plan for co-operation between the colleges and industry, and it may be possible for the Council to follow this up and, either by the plan that Dr. Chapman proposed or by some other, see whether it is not possible to make industry rather more articulate as regards the type of training which it prefers.

Many engineers have to design and plan works, or to select both things and designs, and such activity involves what I would call "engineering decision." Engineering decision arises out of engineering planning, which is the application of science in an economical manner to material things. The point of the phrase "in an economical manner" is rather overlooked in the schools. Years ago I conducted a crusade on this point, and in one of the books of reference which I consulted I found the remark: "So keen are buyers on buying the cheapest thing that the principle of supplying the least amount of material pays from the manufacturer's point of view." Did some of those buyers have no engineering education, or did they have an engineering education and yet learn nothing about the question of costs? It appears that the school should teach something about design in relation to requirements, alternative plans for meeting those requirements, and selection among those alternative plans. An eminent engineer used to train his men to put three questions in regard to any project which was submitted. The first was, "Why do anything?" The second was, "Why do it now?" The third was, "Why do it in that way?" If those questions are applied, very few impracticable schemes will be approved. As a practical suggestion, if in any discussion of design some of the students will take upon themselves the part of the buyer, the economics will probably come out in the ensuing wrangle.

Mr. E. B. Moullin: The education of students who expect to become electrical engineers is not quite the same problem as electrical engineering education. Some young men know that they want to become engineers; others start on such a course almost by chance. By no means all who finish such a course become engineers, and surely it is right and proper that this should be so. The boy who knows from childhood just what he wants to do is often commended, but, since he decides without knowledge or experience, his decision may denote only a set and unenterprising mind.

Clearly it is the teachers' business to give an education in science with a strong trend towards engineering, and something which will have educated a man's mind whatever he becomes afterwards. Plato told us that the purpose of education was to enhance a man's awareness of and increase his pleasure and happiness in life. Those who have the patience to achieve this will *ipso facto* be more able than others to earn their own living. What is most urgently required by the young man at the end of his period of training is a good education. Time in a university is short, and the courses are hard and exacting, so that there is not the time for formal instruction in the history and thought of mankind. The students of the old universities have an advantage in this respect in that they live an intimate collegiate life, and the benefit which they obtain from this close intercourse is enormous. Science teaching should be as broad as possible, a condition not always met in engineering schools. This is necessary because in a few years' time the student of to-day will have arrived at the stage when he will have to receive the reports of many others working under him; and when that time comes, the phenomena which to-day are still in the realm of pure physics will have become industrial processes.

Mr. W. E. Highfield: When discussing this problem it is essential to have some idea of the numbers of engineering students in this country. In electrical engineering there must be fully 5 000 students, of whom, say, 700 are in the universities. If students in mechanical engineering are included, the total will probably be 12 000. The general education and the technical education in this country seem to be sound except in two respects: First, there is little or no liaison between general education and technical education. Secondly, co-operation is lacking between the educational authorities and the public, as, for example, in connection with the introduction of the School Certificate Examinations and the National Certificates in Engineering. Employers often knew nothing about these plans until they had been started, and if a prospective employer does not know the significance of a student's certificates the schemes lose much of their value.

The long time for which the student stays in the university or educational establishment defers the day when he has to shoulder responsibility. The result of this is that the customers come to believe that their affairs cannot be properly looked after or their plant properly erected by men aged, say, 22 or 23. This point of view is a wrong one; it should be a matter of congratulation that a man has achieved competency at so early an age.

Nevertheless, the principles on which all our schools and colleges are founded, namely that the school or the college should remain a separate entity, the principal of which is supreme, without any financial interest in the results of the establishment, should be retained. If that is ensured, and if adequate liaison is maintained, there is little fear that the energy, the spontaneity, the spiritual qualities which have so distinguished our schools in the past, will not serve us equally in the future.

Dr. L. G. A. Sims: In all educational matters it is essential to remember the necessity of infusing enthusiasm into the students, and of ensuring that a similar enthusiasm is present in the teacher. For the latter reason, the suggestions made by Dr. Fleming are very welcome, as there is nothing more likely to stimulate enthusiasm in the students than, for instance, a few actual examples from the test-rooms of the large manufacturing companies.

Sir Noel Ashbridge: In the course of interviewing a fairly large number of students who have just completed their technical college or university education and have either had no works experience at all or only about a year's practical experience, it is remarkable that at least 60–70 % of the applicants say that they prefer "research" to any other branch of engineering. The majority of the remaining 40 % say that they do not know which side they wish to enter, and it is probable that none of them have any appreciable knowledge of the organization of an ordinary large engineering works. It would be a great help if during the process of their technical education students were told what is the routine and method of organization of a large manufacturing or operating concern.

One frequently finds that a student has spent many hours in laying out a design for a 15 000 kW power station, but it is important that students should be instructed in the proper drafting of specifications. Such matters cannot be left to be acquired during practical training, because those capable of giving adequate instruction are far too busy with other duties.

It seems very probable that there must eventually be a much closer drawing together of the industry and the teaching profession. In the years to come electrical engineering training will possibly follow the practice of the medical profession, where the hospital and the teaching staff are under one organization. It might be that the engineering colleges stopped at the intermediate degree stage, and that the students then passed on to a combined college and works course, where they would be taught partly by the teachers of the colleges, as at present, and partly by the staff who are actually handling the contracts in the works.

Prof. W. Cramp: The scheme of training outlined in the first paper appears to be too circumscribed. Birmingham University has always taken a wider view, and it has never been possible for a student to get his first degree there—even an ordinary degree—in less than 4 years after matriculation. This policy gives time for workshop training within the university walls, and for a broader basis of fundamental work. Also, the work of the final year need not be limited to a particular branch of the profession. This is a very important matter of principle, for few men know into what branch of the industry they may enter or ultimately drift.

The education of the university student should not be confined to the merely useful, and specialization should be no part of a degree course. The university should stand to the undergraduate for more than the mere thoroughness of its professional training. It should embrace contacts in the Union, the games field, and the hostels or rooms, with men of other faculties, with other interests, and with widely divergent views. In short, it means a life to be lived—not just a time for acquiring specialized knowledge. A university course should produce men with more background, culture, and character than can be possible at any technical school. This is too often forgotten by students and parents; but, nevertheless, it constitutes the main claim for the universities and especially for those with residential colleges and halls. In this respect, the external degree of the University of London is, in my opinion, not a university degree at all.

Whilst the first paper only touches upon the qualities of character and personality which the period of training should foster, the second paper insists upon these almost to the exclusion of all else. There is no doubt that the inadequate development of the physical side in the modern university is lamentable. In some cases this is due to lack of facilities, and even when that is not the case the curriculum is often so heavily loaded as to leave little time for such amenities. Moreover, in many instances the length of the daily journey renders participation in sports and pastimes very difficult.

In one respect the author of the second paper appears to contradict himself. Failure in examinations due to unwillingness to work at uncongenial subjects is condoned, but stress is laid on the importance of the foundations of character. Surely the determination to master an uncongenial subject is one of those foundations, and is called for daily. Is it to be supposed for a moment that Faraday liked poring over the accounts of the Royal Institution? Yet see how beautifully they were kept! Again, it is suggested in the second paper that technical knowledge can swiftly be acquired in later life. It is to be feared that knowledge acquired in that way is only superficial and carries no conviction. It produces men who are nearly always the second-rate technicians for whom there is little room in industry.

The desirability of confining the technical studies to fundamentals is a most important point, felt by every professor of electrical engineering, and too much stress should not be laid upon methods of production and upon costs.

The ideals of higher education can be expressed in the following seven short clauses:—

(1) All education is of three kinds—of the hand, the head, and the heart; or of muscle, mind, and manhood. Of these three H's (or M's), much attention is paid to the second, and some to the first. The trouble is with the third.

(2) Training of the hand and head can to some extent be carried out by mass-production methods—by lectures, and by laboratory and workshop courses. Training of the third kind can only be imparted by personal influence and example. It controls conduct. It is not subject to reason, but is an affair of emotion and of sentiment.

(3) Booker Washington has rightly said "I am convinced that there is no education which one can get from books and costly apparatus that is equal to that

which can be gotten from contact with great men and women."

(4) Any young man to be educated as an electrical engineer should be placed in surroundings where, with others of his kind, he would be in intimate contact with a tutor who possessed not only scientific knowledge but also culture and, above all, wisdom.

(5) To provide such amenities involves a vast expansion of the tutorial system and an increase of residential colleges. It cannot be done at the modern universities without expense, which, at present, is regarded as prohibitive; but it is, nevertheless, the only way to obtain the men whom the world needs.

(6) Professors, tutors, and teachers, are at present selected on account of their proved professional ability, which is quite compatible with little culture and less wisdom. Tutors should not be appointed unless they showed much more than pre-eminence in scientific knowledge and research.

(7) An ideal tutor would show to his pupils the way of happiness in their life's work, instilling reliance upon internal rather than external authority, and an understanding of truth which would lead them to show the utmost consideration for others, to produce without possessing, and to act without hope of reward: for the qualities of the willing fag are higher than those of the lordly prefect.

Mr. L. W. Phillips: It is to be hoped that there will shortly arise a closer relationship between industry and education which will result not only in a modification of the educational system to meet the needs of industry but in an inflow of the ideals of education into the realm of industry.

The papers emphasize at least two points. The first is the necessity for the unity of education; education cannot be separated into primary and secondary and technical, since each reacts upon the other. The second point is that there is a relation between life and character. Engineering has done more than any other profession to change the life of the people; and that change affects not only social relationships but also moral characteristics. There is thus a great challenge to the engineering industry to react on the side of character.

The post-certificate years at school are important, and there should be some relationship between the school and the works at this period, because this would make it possible for a boy from a secondary school to enter works of various kinds in order to decide the kind of profession he would like to follow.

I feel that the university has something to offer which the technical college cannot. A student in a technical college mixes only with those who are interested in his own profession; he does not get that broader outlook which is developed in a university from mixing with many people who are going in for professions of different kinds.

With regard to physical training, Lord Horder said a short time ago that the best kind of physical training was exercise without exercises. Our activities should be shaped in such a way that we led a natural life and thus avoided the necessity for extra "physical jerks" to correct something which should not exist.

Universities should have professorships of fundamentals, presenting the whole idea of knowledge, both technical and scientific, to students in such a way that they obtained a grasp of fundamentals applicable to a broad field of engineering and industry.

The world is changing rapidly and, if the nineteenth century and the beginning of the twentieth saw the mechanization of life, the remainder of this century is going to see the humanization of life. The tremendous changes which are going to take place in industry will not come from the top but from underneath. Millions of people are going to demand a higher standard of life, and demand conditions which will make industry more agreeable and life more worth living. Students at the universities must be given a knowledge of social relationships in order that they may take their part in this revolution.

Prof. R. O. Kapp: Great stress is being laid on the importance of character, and this implies that the character-training given by educationists is not as good as it should be. It is difficult, however, to see how the present system of training engineers is responsible, and it is hardly to be believed that improvement in this respect can be achieved by a lowering of the standard of degree examinations and encouraging students to devote more time to athletics.

Turning to details of the course of training, mathematics of all subjects ought to be taught on a tutorial basis. The present matriculation standard of mathematics, whether it be on the classical or on the scientific side, is not suitable for the engineering student. It may be suggested that a solution would be to let the student have another year to improve his mathematics; but in the last year at school he is taught by men whose chief qualification is an honours degree and an ability to do things which are so far beyond quadratic equations that they are not necessarily at all adapted to elementary teaching, and certainly have not the specific qualification of being able to deal with immature minds.

Prof. B. P. Haigh (*communicated*): A well-established principle of general experience and of education is that we learn most effectively from our failures. In college laboratories, failures are produced artificially under close observation so that lessons can be learned with greater confidence; and in college lectures and tutorial work, and even in examination questions, the incidence of natural laws in causing historic disasters can be studied calmly and in the light of accumulated knowledge. Nevertheless, a period of practical training is essential after college training. It is very desirable that graduates should spend a period in the repair shop; and it may be of service to employers to point out that a young graduate may be a very useful member of a repair squad.

Mr. I. O. Hockmeyer (*communicated*): The experience of a young graduate who has only recently entered industry is that specialization must be avoided, since a young engineer must be prepared to take any job that is forthcoming.

Mathematics and languages are overstressed, but mechanical engineering subjects are essential. A sandwich system probably provides the best training under modern conditions.

Dr. L. E. C. Hughes (*communicated*): The problem of education is to induce the individual to think consistently and accurately for himself, and this can only be effected by providing him with mental and physical material to think about. His best thinking is performed with material which he likes best, and it is therefore of the greatest importance to find out major interests as early in life as possible. This can be done by noting the reactions when the individual is brought into contact with activities which may possibly appeal to him and develop his several talents, since it is along these lines that his several special intelligences, as well as his general intelligence, will be exercised. Thus, on the average, nursery-school children maintain their superiority in intelligence quotient over all others. Since we must all be taught other subjects than those in which we do our best thinking, these other things should be related to them and presented as essential support. It is comparatively easy to determine whether a youth is likely to succeed as an engineer, and in electrical engineering there is a greater range, from the purely practical side of production to the most advanced mathematical theory, than in most other branches of engineering. The industry has to decide how early in life it is worth while seeking its future recruits, and what sort of life it is willing to offer them in competition with other activities when the individual can safely think for himself. Whatever the medium of education, whether it be scientific or otherwise, the end must be freedom of thought and a capacity to withstand propaganda.

Prof. J. T. MacGregor-Morris (*communicated*): Emphasis should be put on the possibilities of developing the personal qualities of the student during his college career. Fifty years ago it was rare to find a university-trained man in any of our engineering works. At that time those holding the higher posts insisted that anyone who aspired to such positions must be really practical men like themselves, and this meant entering the works at the age of 14 or 15 and, primarily, becoming proficient workmen. Later, some works managers of wider outlook tried a few college-trained men and found that the time devoted to the works training could safely be reduced to 2 or 3 years, during which such men passed much more rapidly through the various shops—the aim being not so much to develop a highly skilled workman, but rather one who possessed a knowledge of men and what can reasonably be expected of them. Those trained in this way, they considered, should be able to take a larger view of life and thus manage a business on more progressive lines.

Now it is generally agreed that man is of a tri-partite nature—body, mind, and spirit. The opportunities at college for the development of the body are utilized by only some 25 % of the students, and to a lesser degree by, say, another 25 %. The remaining 50 % trust to luck and get very little exercise—though one is glad that the matter of congenial physical development is now receiving more attention. It is not enough to have a well-trained mind in a well-knit physical frame, but that this mind must be directed by ideals, which can only be true if the spiritual side is continuously developed. This development must largely be a matter for the individual, but it is not one whit the less important because of this.

Mr. E. O. Taylor (*communicated*): In view of the importance of modern languages, college students should be recommended to spend their summer vacations in foreign travel rather than in an engineering works in this country. Although the works experience gained during such periods is undoubtedly useful, much of the work done will necessarily be of an introductory or routine nature and therefore of limited value in connection with the studies of the succeeding year at college; on the other hand, however, the opportunity of spending 8 to 10 weeks abroad learning a foreign language, obtaining a very valuable broadening of outlook, and also possibly acquiring some engineering experience by visits to foreign works, is one which will probably not occur again during the lifetime of the engineer until after his retirement. The question of cost may of course arise, but with the various organizations now available to students much may be done for as little as £10 or £15.

A further point to which attention might usefully be given is the provision of facilities for post-graduate work on specialized subjects in the evenings. At present any graduate who wishes to make a detailed study of the particular branch of engineering upon which he is engaged must do so privately.

Some training in the art of public speaking is also a very desirable attribute.

Prof. W. Arvon Wales (*communicated*): The subject matter of teaching is in urgent need of rationalization.

[The replies of Prof. Fortescue, Col. Fraser, and Mr. Clough, to this discussion will be found on page 184.]

ABRIDGED REPORT OF THE DISCUSSION BEFORE THE NORTH-EASTERN CENTRE, AT NEWCASTLE, 22ND NOVEMBER, 1937

Prof. W. M. Thornton: Fifty years ago students taking classes in technical schools started with a knowledge of their job. The great majority of what may be called the manager class served their time, many while attending evening classes, and a few emerged and went to universities or technical schools. They made, as is well known, very good engineers. The system of education of engineers was built up by such college-trained men—for example, Rankine, Unwin, Ayrton, and Perry.

About 40 years ago there was a great discussion in Germany on this subject, and the conclusion reached was that the proper training for an engineer was that he should leave school about the age of 17, then go into works for 1 year, and then do what is equivalent to university work for 3 years, with works in the vacations. That is the method still used in Germany, and is certainly the method being used to-day on Tyneside, perhaps more largely than any other.

The idea of part-time training is a recent development. That and the system of National Certificates have very largely modified the way in which candidates enter The Institution. With regard to research, experience shows that for the few who are capable of taking it, it is the most valuable training any student can have. Men start on work of this kind as students, and end as men. They learn in that year to take responsibility and to think for themselves. It is quite the most formative thing of the years of a student's life.

Mention of physical training has been made, but I think the large part that games play in university life has been underestimated.

Mr. T. Carter: An adequate command of English is an essential part of an engineer's education, and it is essential that he should have positive direction in how to become expert in this matter. It cannot be assumed that the average school teaching takes anyone to the end of the sbject, however thoroughly it may treat it. The work must be carried on. It is too much taken for granted that because a student lives in an atmosphere of English, he will infallibly use it aright; the truth rather is that, as with every other tool or instrument, both instruction and practice are necessary, and the more the practice the more skilful becomes the use of the language.

There are two main ways of using words: the oral (commonly, though wrongly, called the verbal) way and the written way. The oral is easier than the written, because to spoken words are added style by means of intonation, stress, gesture, frown, smile, and so on, whereas the written word must depend for its intelligibility far more on the style that comes from such things as arrangement, layout, and properly considered punctuation.

Language is a convention and there must be rules about the use of words. The mastering of the rules is far from easy, and it is perhaps particularly difficult for engineers, dealing with highly technical subjects, so to express themselves in their letters and reports that their words can bear only one interpretation; but it is hard to find evidence of attempts at training in the hence more necessary kind of style that, including correctness, may also win a reader's interested attention rather than his merely casual perusal. Here is where educators may take a hand. They can at least see that written matter prepared by their students is criticized as literature; but they should also give definite instruction with the object of making it good literature. It is said that there is no time for these things. It might safely be replied that it is better to be a little less learned as electrical engineers if we could thereby become a little more learned as human beings.

Prof. J. C. Prescott: It is interesting to note the general opinion that university courses in electrical engineering should concern themselves almost entirely with fundamental principles. It should be remembered that engineering, together with a number of other subjects, is comparatively new to the universities, and that the engineers, among others, are reaping in the universities the fruits of many centuries of academic experience and tradition. Engineers can make an important contribution to the corporate life of their universities, and the benefit they derive will be greater in proportion to the benefit which they confer. Discussion among students of subjects outside their own academic curricula is an important part of the university education for all students, and is one which engineering students are rather inclined to overlook.

With a 3-year course as at present in vogue in most universities a comparatively limited selection of subjects is possible. Where a 4-year course for students in electrical engineering is given it works admirably, but of necessity it must postpone for one more year the wage-earning possibilities of the students, while at the same time increasing the cost of their academic course. Whichever is followed, it is essential to keep alive in the student his creative impulse in order to make his studies more real and immediate to his mind and so preserve his freshness of outlook.

Mr. James Dickinson: The university courses have been successful in the past and have proved capable of adaptation to changing circumstances. A specific and definite training for the responsibilities of general management should now be included. It is difficult to define management satisfactorily, but it should include technical, commercial, financial, and administrative functions. The statement of my reasons for this addition must be brief.

While it is often the impression that university staffs do not appear much to interest themselves with the world outside the walls of their own colleges, yet I know it to be a false impression. The trend of world affairs is a matter for serious thought at the university, and the tendency of world movements in one's own branch is a particular study. An adequate training in it should be a preparation for filling posts of high executive responsibility. This plan was started in America 8 years ago as an experiment, owing to the increasing size of industrial units. A similar condition arises in industry in Britain, and has resulted in a rapid change that bids fair to go on with increasing momentum. These developments have altered the status of management. It has now a professional status in many factories, works, and stores, and what is most significant to engineers is that the function of technical knowledge is now greatly increasing in importance in relation to the other functions that are included under the title of management. At present our available courses in electrical engineering do not include anything of this economic nature. The students are not being assisted during their university careers to equip themselves for posts of high executive responsibility.

So far, in applied science, university training has been mainly concerned in the fundamental principles. The electrical engineering industry is lagging behind some other industries in taking forethought regarding the training of personnel. Certain large-scale electrical engineering works are conducting internal classes for apprentices, but few include in those classes any training for management. It would appear that the foundations should be laid at the university and developed in the post-graduate years while the student is actually in a works. The Institution introduced in 1934 into the Graduateship Examination a subject entitled "Engineering Organization, Management, and Economics," but this has the same shortcomings from the viewpoint of the scientific training of personnel.

The provincial universities, unfortunately, generally have inadequate playing fields for games and athletics. This does not mean that the facilities afforded by the universities at present are all being used by the students. Far from it. It means that if every student wished to be included in some sort of game at the same time it could not possibly be arranged. Too many students come into college at the last moment in the morning and leave again immediately they have finished their lectures. The athletic activities of colleges are borne by a small percentage of the total students, but of the engineers a very high percentage take part in all college activities.

Mr. J. A. Harle: The type of training required by a young engineer is mainly influenced by the side of the profession that he intends to adopt. For a technical or research worker, an approach via a university and student apprenticeship is undoubtedly best, as the university training gives a better foundation in fundamentals. It is preferable for the student to enter the works first and then to proceed to university. He should take his full share in university life, officers' training corps, and so forth, and then complete the practical training by vacation work and a final period in the works and offices.

For draughtsmen a works entry is desirable, with a sandwich course at a technical school, and then completion of the apprenticeship on the drawing board.

It is extremely difficult to forecast the best entry for designers, as these are likely to be recruited from men trained as either of the foregoing classes. Usually, students trained at the university do not desire drawing-office or design work, but when a true aptitude for design is present and recruitment to design work takes place it is likely that the better designer will be produced from the university-trained man.

For sales work, the entry of different types of men trained in either of the foregoing classes is desirable, and equally good material can be recruited from each class of training. Recruitment for managerial training should only be made after completion of several years in the organization, as only after a complete knowledge of the individual's characteristics is gained can a decision be safely taken as to a man's ability for management. For example, there is a tendency at times to judge a man on the sports field rather than on his alertness, balance, and breadth of view on his job, and these judgments cannot be trusted. The ability to keep a large number of problems progressing, urging this one or that one at the right time, co-operating and becoming a leader in a team of other workers is a better basis for selection for management than the ability to score a try. Unfortunately, education alone cannot make leaders; it requires a natural ability, and it is usually found that those who have it will be a success in whatever they undertake, whereas those without it appear doomed to be followers in whatever task they undertake.

Mr. W. T. Maccall: Intelligence tests and the services of the Institute of Industrial Psychology will usually give reliable information as to whether a boy is suited for any given profession.

With regard to the systems of training, experience in the North-East Coast area favours the sandwich system when opportunities for practical training can be found. The actual subject matter of the courses—for example, such questions as the inclusion of a modern language—must depend upon the demands of the industry. But all schemes should have an element of flexibility.

An extension of the system of allowing part-time students to attend their technical colleges during the day as well as in the evening is very desirable.

Mr. A. O. Hünter, jun.: It is preferable for a boy who is proposing to enter the electrical engineering profession to spend at least 2 years at school after the year in which the School Certificate examination is taken. These 2 years should be spent in the study of mathematical physics, for a knowledge of this subject constitutes a valuable tool in the hands of the young engineer.

University regulations should not be too insistent on even Honours students passing in every subject.

Mr. E. O. Wheatcroft: The training received in the works is essential, in that it enables a student to understand and to get on with people he may not like and with whom he has little in common.

[The replies of Prof. Fortescue, Col. Fraser, and Mr. Clough, to this discussion will be found on page 184.]

ABRIDGED REPORT OF THE DISCUSSION BEFORE THE NORTH-WESTERN CENTRE, AT MANCHESTER, 4TH JANUARY, 1938

Dr. Willis Jackson: The several discussions which have taken place during the past year on the subject of industrial personnel are evidence that the present provisions for the education and subsequent training of this personnel are not proving fully adequate to meet the needs of the industrial situation. No one will doubt the difficulties inherent in the attempt to effect a solution, since though there appears to be fairly general agreement as to the qualities which the young engineer should possess, their relative importance is very difficult to define. Several of them lend themselves to development by external influence to only a limited extent and their precise measurement is in most cases beyond our present powers. Perhaps the position would be simplified if one knew how an American firm arrived at the following specification for its prospective managers and how it carried out the necessary measurements by human material. In assessing the results of interviews the following weight factors are adopted:—

Intellectual honesty	Indispensable and not weighted
Imagination ..	35
Judgment	18
Personality	17
Knowledge	13
Experience	12
Energy	5

The low marks given to energy signify, presumably, that managers are expected primarily to organize the work of others and not to be unduly active themselves. Certain of the desirable qualities, however, can undoubtedly be developed, and the difficulty is to obtain general agreement as to how this can best be done and, in particular, as to the degree of responsibility which industry itself should accept for their development in its recruits.

Dealing only with the university-graduate type of recruit, since it seems reasonable to expect that the universities should be the source of the greatest proportion of those men who will ultimately rise to the highest positions of technical and administrative responsibility, the extremely rapid growth of fundamental knowledge and technical development has produced a situation where it is no longer possible for the universities to supply men suitable for immediate use in any technical capacity in industry, and yet this is still frequently expected of them. The deficient national provisions for that broad practical training and technological instruction which are a necessary supplement to a university course necessarily react on the type of course which the universities provide; and the existent university plus post-graduate apprenticeship, and the works plus technical institutions schemes, are becoming more and more alike. This is disturbing, because the university ought to be able to fulfil much more effectively than any part-time technical course the educational function of assisting men to read and think clearly and critically about those branches of pure and applied science which bear on the practice of engineering, and of affording opportunity for these men to see their intended career and themselves as individuals in correct relation to life in general.

It is especially desirable that attention should be given to what might be called " everyday " physics and to those recent contributions to physical knowledge which are likely to react on industrial development, since this knowledge will be acquired only with difficulty, if at all, once the man becomes immersed in acquiring the technological knowledge appropriate to his intended sphere of activity. Also, the undergraduate engineer should be encouraged to take an early interest in economics and sociological questions.

It should be the particular characteristic of all university men that they inquire deeply into whatever matter, technical, administrative, or otherwise, with which they are called upon to deal, and that they are very critical of the validity of their own and other people's deductions, the result of being forced back continuously upon fundamental issues during their university course.

Reference during this course to engineering technology is desirable, but should be intended only to illustrate the general trend of engineering development and to prepare men for the subsequent realization that many factors can arise in practice to affect the straightforward application of scientific principles.

The university course, however, constitutes only one part of the preparation of a man for a position of engineering responsibility. It requires to be linked in the closest possible manner with suitably organized vacation courses and with a course of post-graduate apprenticeship in industry, which affords full freedom for the graduate to select the branch of engineering work that interests him most, and opportunity for him to acquire not only the broad practical experience but also the technical knowledge appropriate to this branch. There is a great need for an extension of the means whereby the knowledge and fruits of experience of those who are at present responsible for directing engineering development, and industrial organization and management can be made accessible to those who are being trained to follow. In this connection it should be possible for the staffs of the technical institutions situated in the heart of large industrial areas and the staff members of surrounding industrial concerns to co-operate in the organization of a series of post-graduate lecture courses linking up the preceding university course, the apprenticeship training, and the requirements of the different branches of engineering activity which a man may elect to follow. It is very gratifying indeed to know that the organization of a number of such courses in the Manchester area is under consideration at the present time.

Prof. J. Hollingworth: It is for employers to decide whether they want real men or merely spare parts for the industrial machine. The latter are probably less trouble and of more immediate economic value to them; but I think that the feeling is growing that a certain number, at any rate, of the former are required, and it is surely the particular function of the universities to provide them. The habit of critical and independent thought, and the constructive application of it, should be the essential functions of a university training, as it is not until these years are reached that the mental powers required for them really begin to develop. From this point of view it would seem that the details of a syllabus are relatively unimportant provided they conform to certain general principles. Engineering is a factual subject, and must always be so, but facts by themselves are sterile things which must be fertilized by ideas before they can grow and expand. Consequently the facts of engineering must be taught, not as mere data to be memorized and used mechanically, but as the source from which all ideas and progress must spring.

These considerations call for what is known as philosophic education, but this does not mean that a student must live in an abstruse world of mathematical formulae; a true philosophical education can and should be intensely practical, in fact it might be summarized in the words " Taking a long view." The old saying that one cannot see the wood for the trees really marks the distinctive failure of non-philosophic education, and it is a trouble from which many students of science suffer severely. Hence, a college course must confine itself largely to fundamentals; a conclusion which has also been reached from another aspect owing to the impossibility of compressing the whole of modern detail technical achievements into a 3-year course. Some specialization is, of course, inevitable; but provided this does not consist of merely loading the student up with an ever increasing mass of intensely detailed technicalities, it can still be given without impairing the philosophic outlook. In fact it can be used to stimulate it, as in his final year the mind of the good student has expanded sufficiently to enable him to appreciate the wider issues involved.

The case of the evening student is rather different. He usually leaves school at 16, thus missing the vital formative years from 16 to 18, and goes into a works where matters of everyday routine are naturally of primary importance. His mind is therefore generally less adaptable and elastic and his training has to be of a more rigid character.

Moreover, although very good men are often to be found among evening students, the greater number of them are of a mental standard incapable of reaching university level; many of them have not even been to a secondary school. The training must therefore be of a type suited to the average mental calibre, far more factual and less speculative.

But, while it is very easy to dilate on what to teach and how to teach it, the actual job is a far more difficult one. It is nearly true to say that nobody can be taught anything. They can only be encouraged to learn, and inspired to go on learning after their official education has finished. This depends on the personality of the teacher rather than on his academic attainments, and the opinion frequently held, namely that a brilliant research worker automatically possesses these qualifications is altogether unsound. There is some justification for the idea that a man who is interested in something outside the ordinary routine work, such as research, will have a more flexible and open mind, and will have ideas worth communicating; but he may be quite incapable of communicating them. Also there is a type of mind on which the intense specialization required for modern research has a narrowing effect, and such a man finds it impossible to take any interest in anything outside his own special idea. Such one-way minds are not infrequent; but a man who grudges every minute taken from his research for his teaching duties should have no place on the official teaching staff. While, therefore, some acquaintance with research is a valuable credential for a university teacher, the interest in and the ability to teach are far more important; and this fact is gradually becoming more recognized.

After all, the students pay the university to be taught, and it is up to the university to fulfil its part of the contract with a reasonable degree of efficiency. A university must carry on research; but, provided it can afford it, the relation between research and teaching should be far less rigid than it often is.

Mr. R. J. Hebbert: The engineering industry calls for technical qualifications and good personal characteristics. This fact suggests the great importance of a right selection at a time probably very much earlier than the age of 16. It takes all sorts to make a world, and in our world of engineering all sorts are necessary and it is essential to get the best of each. This necessitates a close co-operation between educationalists and industrial employers who are, after all, the customers for the former's products. A good deal can be done by schools very early in the lives of the boys in vocational selection and training. This does not necessarily involve early specialization, but it is good for a boy to know, while he is young, at least, where he wants to go.

Present examination standards are apt to be misleading, particularly if they are considered without relation to many other important factors. There is a good deal to be said for something more practical in the way of examinations which reproduce the conditions in which the young engineer will find himself when he comes into business life.

University graduates in electrical engineering tend to become electrotechnicians rather than engineers. They know the details, but in simple engineering principles they are decidedly shaky. Some experience of the drawing office is of the utmost importance to the average engineer, and all young engineers entering industry should avail themselves of that experience as far as they possibly can.

Mr. A. G. Ellis: Experience in the selection of candidates for entry to electrical engineering works leads to some apprehension with respect to the staffing of the electrical industry at present and in the future. Unfortunately, relatively few of the young men who come into engineering are real inherent or born engineers. Many of these men would have made equally good or equally mediocre careers in any other profession. They often lack an adequate power of expression, both in speech and in writing; and when a vacancy occurs involving a position of responsibility, it is often the right man for the job who is difficult to find, in spite of the fact that many of us have a large reserve of young men, either trained or in training, to draw upon.

Experience of a very complete scheme of practical training suggests that these defects are attributable to the raw material or to the shaping of it at the educational institutions. The educationalist may be able to blame his raw material, which the practising engineer cannot do, nor can he bury his mistakes. Now, in connection with this vital factor in the problem, what, apart from the college entrance examinations, are the educationalists doing in the matter of selecting their raw material? And in the university courses, what is being done nationally to make and to keep contact with industry and its requirements? Present-day courses do not differ a great deal from those of 40 years ago. They appear to get rather stereotyped and superficial, owing, I suppose, to the large amount of ground which they try to cover and the complexity of the subject on account of the tremendous development and progress of electrical engineering since it became an industry.

It is gratifying, therefore, to hear a demand for a return to fundamentals. I believe that at least one of the universities already professes to teach the students only the principles of engineering science, leaving the application of those principles to the works-training period. If this is a correct policy, it would be desirable to give the students certain limited courses of lectures in engineering practice, with a view to giving them some acquaintance with practice and to stimulating their vision, though not with the intent of endeavouring to specialize them whilst they are at college. Such courses of lectures should be given by visiting lecturers who are practising engineers of as high eminence as possible, on the same lines as has been the custom on the Continent for many years with mutually beneficial results.

With reference to evening classes, these are a necessary evil, which will be with us until some better scheme is evolved for giving educational advantages to lads of brain but little means. The strain of works all day and study (mostly) all evening is so great as to tire these young men out in youth before they are really grown up. One admires the grit of these youths, and especially of those of them who ultimately get into fairly responsible positions; but the majority of them suffer from the handicaps of that heavy and monotonous grind in their youth. The youth may deepen his mind, but he has little time or opportunity left to broaden it. The plan of holding part-time courses in the afternoon or, alternatively, a system covering all the 5 or 6 years of training whereby the lads study half the week at the college and half the week in the works is a most desirable one. Some enlightened firms grant facilities to their "trade" apprentices for part-time day study at the technical college; but this is not much more than a gesture. What is required is a revolution, and it is certain that the educational experts in the works and the colleges could devise a satisfactory scheme if they gave their minds to it.

Mr. J. G. Armitage: Students who cannot afford a university training must acquire their technical qualifications by attending evening classes. The effort to obtain a degree in this manner, though well within the capacity of a few, is outside the mental and physical capacity of the majority and is strongly to be deprecated. Excessive time at evening classes tends to narrow a student's outlook on life at a period when he is most receptive to broadening influences. He is deprived of the leisure time to go in for such interests as politics, music, or drama.

Three evenings per week should be the maximum permitted by those responsible for the lay-out of evening courses, and the policy of employers affording facilities for student apprentices to spend one or two afternoons per week at the technical institute should be extended. The alternative to a degree is to sit for examinations qualifying for Graduate Membership of The Institution of Electrical Engineers, and employers placing appointments should regard the Graduateship of The Institution as equivalent to a degree. In many cases it represents even greater merit when the circumstances under which it has been obtained are taken into consideration.

It is difficult to lay down hard and fast rules for a course of training for an engineer, because at the outset of his career a boy has no idea what branch of engineering he would like to follow; and, moreover, as the years go on, his ideas change. In most cases the boy who enters the electrical industry does so from an inborn manual ability coupled with a fascination for the manner in which electricity is used in the service of man. Do many of these boys find themselves in jobs in which they can give expression to these traits? Experience shows that previous ambitions have often given place to a feeling of bitterness or disappointment when the engineer, after graduating, finds he is not able to attain the financial status which is enjoyed by his former friends. His training, then, particularly in its early stages, should be planned along general lines, in order to give him an insight into the various branches which are open to him. The inclusion of at least one modern language is desirable.

Mr. A. H. Banks: The problem of the man who has grown up with his job and is about to be launched on the world to assume a responsible position has to be faced; and he presents a constant difficulty.

It is the considered opinion of both sides of the supply industry that one of the root causes of the trouble is the disgracefully low salaries at which academic qualifications are rewarded in some industries. Many employers think that because a young man has got letters after his name he is so anxious to get a job that he will take 30s. or 35s. a week in order to have a chance of getting some experience. If that man is paid a sufficient salary to maintain himself during his final years in that dignity which ought to attach to the profession he is seeking to enter, he will be independent of his parents, and he will be a far better man than one who is receiving doles from his parents to help him to work out his education.

Mr. H. J. Shelley: Co-operation between those in industry and the teaching staff in the setting of examination papers is not a practical proposition, since the former generally have not the necessary experience nor the time at their disposal.

Almost all educational courses to-day, particularly in technical schools, tend to "pump" facts into students too much, and to give them too little time to think for themselves.

There has been some mention of the university man as against works training and the part-time student, with reference to the relative functions of the university. It is true that a university student, giving his whole time to education, has far wider opportunities of getting down to the job of educating himself than the boy who has to put in his best work either in his own time in the evenings or —if he is one of the few fortunate ones—when he is released for part-time day study. But the boy who has the courage and the grit to go on year after year—sometimes from the age of 14 to 22, 23, or 24 and more—in evening classes for three evenings a week on top of his day's work, has undergone a very good period of sound character training. If he sticks it out and has the fundamental inherent qualities of personality to start with, he makes a first-rate man in the end. Many of our leading engineers to-day have been trained in that way.

It is easy to find fault with engineering education, and no one would claim that the present system is perfect. It is not; and let us hope it never will be. It is now 6 years since the President of the Board of Education set up a Departmental Committee, under the chairmanship of Sir Dugald Clerk, to inquire into education for the engineering industry. The inquiry was made in co-operation with the associations of engineering employers, and some 260 leading members of the engineering industry—that is to say managing directors, works managers, and so on—were interviewed. All kinds and sizes of engineering firms were consulted; and in Lancashire and Cheshire some 75 were seen. The report was written on the results of these inquiries, with, generally speaking, very little adverse criticism. In the course of those discussions a good deal came out which resulted in a certain amount of very interesting development—for instance, the schemes of associated certification by the industry and the technical colleges in Coventry and Birmingham. Nothing, however, was done by the industry as a whole as a result of the report.

At the London discussion the suggestion has been made that The Institution should set up an Education Group; but it is perhaps more important that the engineering industry, particularly the electrical engineering industry, should regard education as part of the whole scheme of engineering training, and should set out to consider what should be done for the future.

It has been suggested that engineers in industry should be brought more into the teaching of the subjects in the technical colleges and universities. A good deal of our part-time teaching in the evening is already done by people engaged in industry. It has also been suggested that courses should be set up on a sandwich basis of half a week in the works and half a week in the college. As a matter of fact there are already a number of schemes of that type. One of the difficulties is the question of "break," and from the point of view both of the industry and of the teacher, this is considerable. If such a sandwich scheme could be arranged whereby, whilst the student is in the works, he is still under some teaching guidance there would be very much more in it. The Joint Committee of The Institution and the Board of Education are not disposed to recognize any course of study which involves attendance on more than three evenings a week. For many this may be too much, and it seems to be too much, but until industry as a whole is more sympathetic to part-time day release, the most must be made of the present conditions. Courses involving two evenings a week during the whole of the year instead of only two terms with three evenings a week are a possible alternative. It could cover as much actual class time, and the student would have very much better all-round physical conditions to work under. The winter session is by far the worst from the physical point of view, and there would be a covering of that long gap from April to October in which, as most teachers think, the students forget everything they have done during the previous session.

Mr. R. Noonan: It is not unusual for a university graduate to seek experience in one or two years' apprenticeship, in going through the shops. This might well be improved if a little time be sacrificed in the shops and more time spent in the drawing office. The young engineer's training could also be improved if the more responsible men of the firm gave some outline of the methods of production, from sales to delivery, so that the student could get his bearings in a particular works.

Mr. W. Kidd: History of the people—not kings—is one of the best subjects for broadening the mind and developing the faculty of taking a long view when making decisions. It must not be forgotten, however, that the man without technical knowledge is not an engineer. Electrical engineering is now such an extensive subject that complete knowledge of all branches is impossible; it is therefore necessary for young men to confine their studies to fundamentals and to give more detailed attention during the last year of study to the section which seems likely to offer them employment.

With regard to the actual courses, two suggestions may be made; namely, that examinations should not involve too much memorizing, and that some degree of specialization is desirable during the last year of academic training. Channels of employment might be used to engage the youths (subject to passing the final examinations) before the last, instead of after it! If this were done, then a large number of youths could devote themselves to a course of study which would be of definite use to themselves and to the community, instead of doing work which may never be used by them after the examination, because, after a struggle, employment is obtained in an entirely different sphere.

The employers can help themselves and others a good deal by seeing that their trainees are given the opportunity of obtaining a reasonably varied experience.

Mr. L. H. A. Carr: The work of an engineer, right up to the end of his life, can be divided into three parts: firstly, the acquisition of information; secondly, the digestion of this and its correlation with information and knowledge already available; and thirdly, the actual output of work. The first two activities are as important to a fully qualified engineer as the last, though in a sense it is only the last he is getting paid for. In student days it is sometimes thought that the principal duty is the maximum acquisition of information. But, on the contrary, students should be encouraged to develop the critical faculty; to compare the different treatment of the same subject by different authors; to be trained as far as possible to express themselves; and, finally, to give an opinion on the different renderings. For these reasons I am in favour of an examination system, because if a student cannot explain to an examiner what he means, he has very little hope of explaining things to other people who have little engineering knowledge; and therefore he has lost one of the important attributes of an engineer.

A student must have a "tidy mind." The importance of this has not been stressed. To come to detail, it is essential that students should understand fundamental principles, and unfortunately many do not. The average graduate and the average evening-class student cannot draw and *understand* a vector diagram such as that depicting the equation $E - IR - IjX = 0$.

With reference to the suggested maximum of three evenings at night classes, under such circumstances home work should be absolutely prohibited.

Mr. C. Anderson: A sense of proportion does not seem to be given the prominence it deserves in the teaching of engineering subjects, and much time is wasted by young engineers owing to lack of this quality. Even older and more experienced engineers occasionally seem to be lacking in this respect. They pay too much attention to some particular feature of a job, such as the cost, the appearance, or the workmanship, to the detriment of the remaining features which are equally important. The universities are apt to forget that their problem is the training of the *average engineer.* The average engineer does not require an extensive knowledge of foreign languages. There is ample literature in his own language, either by British or American engineers, for his purpose. Similarly with other classical subjects. On the other hand, freehand and engineering drawing do not generally receive sufficient attention in the training, especially as regards the reading of drawings. It must be remembered that a very large proportion of practical engineering is concerned with either the preparation or interpretation of drawings and diagrams.

A great deal has been said in the discussion about the university versus part-time training. There is no doubt that, other things being equal, the university training is a great advantage. It must be remembered, however, that the "weeding-out" process of the undesirables is much more severe in the part-time training than is the case in the university training. For instance, out of 100 students commencing the Associateship course in Electrical Engineering at the Manchester College of Technology, only 7–12 % complete the course; but this small number can usually be relied upon to make good engineers.

Mr. J. W. Thomas: Engineers can congratulate themselves that they are able to discuss the question of their own training. In that respect they are in a better position than many other professions. For instance, there is no method whereby lawyers or doctors can come together in a meeting such as this and discuss the improvement of their own training. It is to be hoped that the result of the discussions which have taken place here, in London, and in other Centres, will be to bring about an improvement in methods of training. As has been said by many speakers, there is room for it.

All engineers should possess the ability to co-operate and collaborate with their colleagues. Industry to-day, and engineering in particular, is a co-operative effort, and the efficiency of industry depends not so much upon the efficiency of the individual units which compose it as on the efficiency of the collaboration which takes place between them. During the last 30 years one big improvement is the increase in the willingness and ability of most engineers to co-operate with one another. Thirty years ago engineers were too much inclined to act as separate units pulling in their own directions and for their own purposes. There was not the team spirit or the *esprit de corps* which exists to-day. Many were nurtured and trained on the principle "Every man for himself," and were doing the best they could for themselves, not realizing that the best interests of the industry did not lie with one man alone but with all as a community. This co-operative spirit can be trained and developed, e.g., by the management. Where there is a team spirit abroad there is probably also efficiency. This spirit can be nurtured also in the university, and that is an advantage on the side of the university-trained man in industry, but there should be greater facilities whereby promising youths can obtain a university training.

Mr. E. Roscoe (*communicated*): It is not certain that the existing systems of training engineers are open to the criticisms levelled at them. If the electrical profession were lagging behind the times, if engineers had failed to meet the demands of their day, then we should expect an inquiry to be held and perhaps should find that the fault lies at the door of our educational system. Such is not the case, however, for electrical engineering and electrical engineers are well equipped for the tasks that are before them to-day, and are ready for the job that awaits them to-morrow. The knowledge and skill of their profession is far in advance of the knowledge and skill of that of other professions who insist on a university education before the profession is entered. The advancement in electrical engineering is not due to the university man alone, for the major portion of engineering is carried on by men trained in technical colleges, and they have done their share towards bringing the industry to the present standard of efficiency. Granted, there is still room for improvement, but engineers, both university-trained and college-trained are entitled to credit for knowing that all inefficiency cannot be rectified by a more fundamental knowledge of mathematics and physics.

The technical college plus works training has produced in the past the right type of man, and this by the very character of the training. The courage of attempting to give up five or six evenings per week for eight months out of the year is, in itself, the hall-mark of grit, interest, and determination, and it shows an outlook that is big enough to succeed in spite of difficulties.

What better proof of physical fitness can there be than that the student has stood up to a test such as this and succeeded? Doubt has been expressed about the facilities for games, etc., at provincial universities, but the technical-college student is apparently capable of looking after himself physically by walking or providing for himself some form of sport in his leisure hours at his own expense!

Mr. Anderson's statement that only from 7–12 % of the students of the Manchester College of Technology are of the right material is surprising. If this result is general, then the 56 millions spent every year on education could be put to better purpose. Actually the material in the schools is still as good as it was in the days when the leaders of the engineering industry of to-day were at school, and we need have no worries about either the system or the results it will produce, so far as the right men for the right jobs are concerned.

A university education may give more fundamental teaching and may make the lot of the student easier during his training, but it is not certain that it will produce the desired effect. It depends entirely on how the student reacts to it. Finally, a knowledge of modern languages is not at all necessary, even to enable an engineer to read literature on his specialized subject. If there is not sufficient electrical literature in the English and American language to train a man for an engineer, he will never be an engineer. A knowledge of medical science might be of far greater advantage than that of a modern language, or even of history, but none of these is essential.

[The replies of Prof. Fortescue, Col. Fraser, and Mr. Clough, to this discussion will be found on page 184.]

ABRIDGED REPORT OF THE DISCUSSION BEFORE THE NORTH MIDLAND CENTRE, AT LEEDS, 18TH JANUARY, 1938

Prof. E. L. E. Wheatcroft: Considering chiefly the place of the university in the scheme of engineers' training, the main characteristics of the university may be summarized by saying that the Engineering Department and, in fact, the whole of the Faculty of Technology are only a small part of the whole. If the university were merely to perform the same functions as a technical college, perhaps in greater measure and rather more expensively, I do not think it would justify its existence and it might easily cease to be. In fact, it is generally agreed that a university degree is the proper channel, if possible, of engineering training for the type of engineers that we have under discussion. It may be taken for granted too that the university is technically efficient; the system of external examiners, for example, necessarily ensures that. But it is what the university has to offer in addition to, and outside, technical instruction that matters very much. There is a quotation which says that the great advantage of going to Oxford or Cambridge is the better use made not of the time in which one works but of the time which one wastes.

There are three avenues of approach to a modern university: from the day school; from the works via the evening school; and from the boarding school—and this order represents roughly the numerical importance of the three classes; that is to say, the day-school class is the most numerous, then those from the works, and those from boarding school are third. A modern university provides proper facilities for physical and social activities, but the difficulty is to get the students to use them. There is no difficulty with that small class who have been to boarding school, because they have already acquired the habit and continue to have a proper appreciation of athletic and social education. There is no difficulty with those who come from industry, for they attain the university with much hard work and are prepared to appreciate what it has to offer, although very often they find the academic work hard, and often they are living on a margin which does not allow them to make full use of university life. There is no difficulty with those—comparatively few—who live in the university hostel. They have a natural *esprit de corps*. The difficulty comes with those—the majority class—who have been to day school and go on to be day students at the university.

All systems of training of engineers are going to stand and fall by the results obtained with what may be called the ordinary engineer. Two years at school after the school-certificate stage is advised by most schoolmasters and, it is now compulsory, or going to be compulsory, that a boy shall spend an extra year after the school certificate before he can matriculate in the Northern Universities. But it is possible for an intending engineer to stay too long at school. It is right for those who are going to be researchers, but not necessarily right for those who are going to take executive or similar positions. Similarly, it may be possible for a young man to go too early to a university, when his mind is still immature and when he is unable to appreciate the possible social and athletic activities provided and may also be unappreciative of engineering science.

One solution for these boys is to let them go into the world for a year between school and university. Let them go abroad; let them go into a labour camp; let them attempt to earn their living; let them go into industry, or, to be particular, let them start to serve their apprenticeship when leaving school and before they come to the university. This plan has already been worked with very great success and is proving very satisfactory. These men come to the university full of enthusiasm for learning, and with an appreciation of engineering which makes their course many times easier, and, what is more, they immediately assume the leadership of those social activities of the university which it is so necessary to emphasize.

Reverting to the details of the courses of training; none of the bodies setting out to train engineers can afford to specialize. Universities must be prepared to take all kinds of boys of all kinds of temperament, who will, ultimately, make all kinds of engineers; some will ultimately be researchers, designers, salesmen, managers, and so on, and the training has got to be adaptable to their varying needs. Now the works apprenticeship is made adaptable already and recognizes this, and most universities have a certain vertical adaptability in the sense that they offer first, second, third, and pass degrees and diplomas, for there is a very wide range of intellectual attainments covered by those different standards. In Leeds University, it is recognized also that a wide choice of subjects is offered to the student in his final year, so that he may visualize himself as the general, or highly specialized, engineer, and may take any mixture of civil, mechanical, or electrical engineering which he may choose. Where possible—because it does involve a certain amount of extra work on the part of the university—that is the right type of course to provide.

Lastly, it appears that it is ultimately the industrialists who will decide what is the right type of education which the engineer is to get. The university, or college, will provide what is wanted, given that, of course, it will not, if it can help it, debase its standards. The engineers in industry should therefore help by saying clearly what is wanted. Their help is wanted, too, in devising such schemes of training that in the British Dominions, for example, British-trained engineers are not ousted by Americans in view of their greater pep, or better training, or whatever it may be.

Mr. J. H. Everett: The opening papers are too exclusive, in that the training of the very large number of lower-grade technical staff is not considered. It is to be hoped that this deficiency will be made good in a subsequent discussion.

The desirable elements of an engineer appear to be character, cultural knowledge, physical fitness, technology, and practical experience. How are they to be acquired? In this country, at any rate, this is an economic problem. Fees must be paid to go to the university, either by scholarships or from the student's own funds. Scholarships are limited and always will be. The selection of the remainder is from those with sufficient money. Are the brains in this country only the preserves of people with money?

A large number approach electrical engineering through industry and part-time education as shown by the number of students who acquire their Higher National Certificates, which are of a high standard set by The Institution. Those students are usually in industry concurrently with their technical training, and that training must take a longer time if it is combined with experience in industry.

Dr. E. C. Walton: There is one point which has not been brought out markedly in the papers or in the discussion, and that is how it is possible for a youth to qualify for Graduate Membership of The Institution by a works training plus National Certificates, the latter being taken wholly by means of evening study. There are four ways of qualifying for Graduate Membership. There is the university degree plus works training, and works training combined with part-time day study leading to an external degree; there is works training plus National Certificates; and, finally, there is the works training plus direct entry by the Graduateship Examination. There must be a large proportion of men going into The Institution by means of these National Certificates, and that part of the work is well worth considering. If the scheme of study set out in Prof. Fortescue's opening paper is to be carried out by means of evening work only, then the scheme is far too ambitious, because, to cover the scheme properly, a course of evening study would necessarily extend over a very much longer period than is thought desirable at present. It would be a great advantage if more students could be released during the daytime to attend part-time day classes. The length of time available for study would be increased enormously, and it would be possible to lay a much more sound and broad foundation of knowledge than is possible by means of evening study only. When students come to evening classes they have already had a full day's work and in many cases have travelled for long distances. Also, as a result of the large demands of evening work, the teachers themselves have to be drawn from industry, and although their work is very good, they are not in such a fit state to give the necessary time and encouragement to the students as the men whose full-time job it is to train these youths. Further help from employers is urgently needed in the matter of releasing students who are undergoing their works training for part-time study.

With regard to the details of the scheme of training outlined by Prof. Fortescue; it is agreed that the function of the laboratory work is to train the student's powers of observation, but in the practical training should not work in the pattern shop be the first step?

Colonel Fraser's opening paper seems to indicate a danger of swinging too far in the direction of not demanding the technical efficiency which is so absolutely essential for an engineer.

With regard to Mr. Clough's paper, examinations not only are a test of the candidate's technical knowledge but are a proof of certain other qualities in the individual concerned—these qualities being, particularly in the case of successful evening students, those of perseverance, courage, and energy. These qualities are very necessary if a student is to stick at the gruelling courses for a large number of years. It is in this respect that examinations, or examination successes, bring to the forefront the men we desire to get into the electrical industry.

Mr. J. R. Rylands: There is a distinction between education in the general sense and vocational training in the particular sense. From the standpoint of the university, it is education and the educational aspect generally that are more important, but from another standpoint vocational training may be considered to be more important.

It has been stated that the university course is generally more philosophical in outlook. Actual experience raises some doubts with regard to this statement, and some re-assurance with regard to present-day engineering courses would be acceptable.

In industry there is some doubt as to whether more stress should not be laid during the apprenticeship period on the acquisition of manual skill, since it is something that gives pleasure to a man.

Industry will not agree that, as a rule, one year of research is at least equivalent to a year in the works. Nor would it agree to apprentices being allowed to investigate costs of production. A manufacturing firm, as a rule, keeps its costs to itself and the department dealing with that aspect of its activities is certainly not open to the average apprentice, more particularly when the firm in question is engaged in competitive work. Even if an apprentice were privileged to record the time and cost of operations in a foundry, he would probably form an inaccurate conception of what was going on, owing to the non-co-operation of the workman.

Regarding Colonel Fraser's remarks on "Technical Bureaucracy"; this kind of thing seems to be happening generally on the Continent. In Holland, for example, no one is allowed to call himself an engineer unless he has passed through the Delft Technical College or its equivalent. Then he may put "Ir" before his name. He is an engineer. He has a passport to a job. The "engineer" looks down with scorn on the people who have not that privilege, and the title has improved the standing of the electrical industry. In Germany the title "Dr.-Ing." confers quite a halo. Things have gone rather far in Germany in this direction, but there is this possibly redeeming feature, that there is an enormous amount of research being done very inexpensively by people anxious to obtain high degrees.

All discussions of this kind end in an appeal for greater co-operation between industry and the educational authority. The difficulty is always to bridge this gap. With closer contacts between industry and the educational system, the problems of technical training would be solved.

Dr. A. W. Ashton: A long experience with technical education leads to the conclusion that a greater number of engineering students should have a works training before they go to the university. It is probable that the cultural value of a works training is lost sight of by many people. Students who have been employed in a works and have gone to the university will find themselves much more at home and much more likely to take advantage of things which the university offers than those who come straight from school.

More co-ordination and more co-operation between the works and the technical college or the university could be obtained in various ways. In many technical colleges the urge to make that contact is very present but, owing to the difficulties which arise in the works, the contact is not sufficiently close.

There is need for closer co-operation between the work of the technical college and the university, because there is very little difference between a large technical college and a university except that the university is free from Government interference and is therefore able to carry out more readily the things which experience has shown to be advisable. In the technical college this is not always the case, and it is often difficult to persuade the works to allow the boys sufficient time for technical training. The difficulty can be overcome by a sandwich system in which the employer takes two apprentices instead of one. One half of the apprentices come for 20 weeks into the college for a full-time course and then return to take the place of the other half who then enter the college. During the 20 weeks that the boys are in the technical school a scholarship of £15 to £20 should be awarded for maintenance. The scholarships are, of course, an additional charge to be borne by the local authority, but the success of the scheme justifies the expense. A few of these boys may become Graduates of The Institution, but the majority will remain in the lower grades. It is to be hoped that a similar discussion of their educational needs will be held in the near future.

Mr. H. Woodward: Many boys are handicapped by a lack of knowledge of what is required of them in the way of qualifying examinations, and others cannot attend a university owing to limited resources. Examinations are necessary, even only as an indication of the fact that a boy has sufficient character to work at uncongenial subjects when he believes it to be necessary.

Mr. R. M. Longman: Mention has not been made of the amount of time and money that an embryo engineer may be able to devote to his training and what return he is likely to receive.

Languages have been mentioned, but except for those having a natural aptitude for them and some real intentions or prospects of using them the time would be better spent in other directions. Specialization has been mentioned in the opening papers. A student going through his training whether at a technical college, university, or part-time course, should not specialize but should rather obtain a thorough grounding upon which he can subsequently build as may be necessary at a later date. Specialization at too early a stage may easily find the engineer stranded. Manual training should find a place, as it not only teaches the proper use of tools but trains the eyes and hands. Individuality and character are all essential. Laboratory work is very essential, but it is important that the arrangements should not be too easy; the students must be made to think and improvise —the best-equipped laboratories do not necessarily turn out the best engineers. The training must encourage the development of common sense or what is better expressed by the term "savvy."

The technical schools and colleges are doing very excellent work with part-time and evening classes, and employers are strongly urged to do their part and give much wider facilities for part-time work at such places of instruction. For those who can afford full time at colleges or universities, a year should be spent at some works before entering college.

Mr. L. Marshall: Young students are often in doubt with respect to their future careers, and the universities and colleges might well have departments whose staffs would interview students and advise them.

Severe steps should also be taken to deal with cynical students of ample means who fail to take their duties seriously.

[The replies of Prof. Fortescue, Col. Fraser, and Mr. Clough, to this discussion will be found on page 184.]

ABRIDGED REPORT OF THE DISCUSSION BEFORE THE SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH MARCH, 1938

Mr. H. Hooper: Every class-room in our universities and colleges should have over it the following inscription: "Useful knowledge acquired to-day makes each succeeding day more productive."

It is a very difficult thing to propose a scheme of education which will suit everyone. A 4-year full-time course seems essential. There are methods of obtaining that by means of scholarships, but I think there should be greater facilities for a link from the technical college to the university which would give facilities to poor boys. One development should be in the courses dealing with management problems, the economics of mass production, and costing and works organization generally. It is gradually being realized that "management" is a science. This will gradually extend into the field of industrial relationships (i.e. between employers and employees). A special technique and a new "profession" may develop to overcome the harshness of our present industrial system and try to bring back some of the atmosphere of the old working master with his staff of craftsmen. This new staff will deal with inducements, monetary and otherwise, factory conditions, spare-time activities, rest-periods, and anything which will help to combat the killing monotony of modern mass-production.

Advance in commerce, on which the whole country depends, requires that boys should enter business.

It is to be hoped that a similar discussion of the education of trade apprentices will be arranged in the near future.

Mr. W. R. Cox: A year before leaving the university a young man does not usually know which particular branch of electrical engineering he is going to follow. His career can generally be likened to a game of chess in which the circumstances change as the game develops and only the best players can see more than a few moves ahead. Education should be as broad as possible to bring out the valuable quality of adaptability which seems to be latent in most men while they are young.

To-day there is a mass of detailed information available in the many branches of electrical engineering and it is hopeless to attempt to learn them all. Fortunately the whole structure of engineering practice is built on relatively few fundamental principles which do not change. It is these which an engineer must know, and know very thoroughly, if he is to be in a position to understand the details of any branch he may follow and eventually to be able to add his contribution to the advancement of the art. These principles include not only electricity but also mechanics, heat, structures, hydraulics, and pneumatics. In addition, a good grounding in mathematics is necessary.

Another most important side of engineering is organization, and this leads to the subjects of finance, economics, and costing. A grounding in the fundamental principles of these subjects is therefore necessary.

Practical work in the laboratory is very necessary and is generally adequately included in most courses. Of equal importance is work in approved workshops. The handling of parts commonly used in engineering such as bolts, angle iron, etc., and the handling of machine tools even in an elementary manner, give a sense of proportion which cannot be obtained in other ways.

Finally, all the technical knowledge in the world will be of little use unless a man's character has been developed along the best lines and the qualities of leadership and good citizenship have been brought to the forefront.

To allow these qualities to develop, a young man's work must not be so full of detail that he has not time to develop these other more elusive qualities.

This leads to the question of examinations, which are now the only "yard stick" which the educational system has for comparing the relative ability of a young man. It is a very imperfect "instrument," as it only measures in one dimension, whereas the quantity to be measured has at least two dimensions. An equally handy instrument measuring in two or three dimensions is badly needed.

Mr. P. I. Kitchen: After many years' experience, Rugby Technical College has evolved a scheme whereby all types of apprentices, including trade apprentices, are catered for with day-time release. The engineering apprentices are of a high grade and do $38\frac{1}{2}$ hours per week in the works and 12 hours in the College. During that time they may take their London University External Degree. Another type of apprentice takes the Higher National Certificate, with a $43\frac{1}{2}$ hour week in the works and a $7\frac{1}{2}$ hour week in the College; and in addition there are the trade apprentices whose working week is similar. It is not to be claimed that the Degree students in the technical college can get that breadth of training for which Prof. Cramp was specially pleading. But they get something which cannot be dismissed lightly. Prof. Cramp spoke of the facilities offered by university Unions for associating with one's fellow-men, but a member of a technical college associates with his fellow-men in real life, and not in the artificial life produced by the university, so that students of the technical college are at least swimming in water! There is another aspect. Engineers cannot get away from costs even in engineering training. The Technical College course costs the student £5 per annum: at a university it costs £200; which is a point to remember.

It is important that during a university or technical college career a student should do something thoroughly, for he can then recognize how far his knowledge of other subjects falls below the standard of that in which he is a specialist. It appears desirable that industrial economics should be treated after the student has been really in touch with a manufacturing organization. Mechanical engineering, on the other hand, should form a large part of an electrical engineer's training.

The development of personal qualities is all important. It is during the years from 18 to 25 that these qualities are developed; maybe they cannot be made to follow any given pattern, but they are developed. In these days in a democratic community when much of the work is not really technical but consists in the persuading of other people above and below to take action in certain directions, these qualities are growing more and more important. It is by no means certain that the school-prefect system contributes appreciably to the development of these qualities.

Examinations, or some other test by which a man must rely entirely upon his own wits to attempt set tasks with a severe time limit, are necessary. Examination of course work also contributes to a correct evaluation of the candidates' qualities.

Mr. H. E. Knight: A complete discussion of the education of the lower grade of apprentices is urgently necessary, especially in connection with those entering the operations side of the industry. They are the backbone of the industry, i.e. the practical lower-grade men. At the moment there are plenty of graduates and partly trained people throughout the country, but the pinch is felt when it comes to the practical men. A recently introduced scheme of training embraces apprentice training closely tied up with the technical institute, known as the "Monotec," and includes courses up to the National Certificate standard, from Grade 1 to Grade 3, which is the ordinary National Certificate year. It is intended that the scheme will be in charge of an apprentice supervisor, who will also act as the principal of the "Monotec." A proportion of his remuneration will be paid by the County Council, and the remainder by the company, and it will be most interesting to see how this is going to turn out.

Mr. R. A. Joseph: Complaint has been made that the universities still produce engineers who have no mechanical sense. At Birmingham that would not be possible, as a student must, in order to obtain a degree, not only take a course in the university workshops but also in a works during a vacation. This is also true of nearly all other universities.

At a conference of university engineering students held at Loughborough in January, practically all the students present were in agreement on one point, namely that with industry's present demands of graduates the course could not satisfactorily be completed in 3 years and so should be lengthened to 4 years, as it now is at a few places. It is agreed that this will be a great financial strain, but it is felt that where this cannot be met by the student, either the Government or the industry must be prepared to provide more scholarships.

With regard to the cultural education at the university, it has been stressed again and again that the engineer who knows nothing but engineering is seldom if ever successful. At the above conference an address was given by Sir George Lee, who laid great stress upon the importance of the development of character and personality. Development is not limited to the early years, as suggested in Prof. Fortescue's opening paper. It can and does occur at the universities, mainly in consequence of the general social activities. Every university now has its Union which is run by the students, and here at Birmingham there is one of the finest in the country. There are about 1 350 students, and of these about 650 avail themselves of the athletic facilities provided. That does not appear to be a very high percentage, but this is partly due to "overloading" of courses—some are very full and do not leave the student much time for other activities. There is also an Engineering Society which is in many ways similar to the Students' Sections of this Institution, holding lectures of general technical interest and visits to local works. The Student Industrial Committee is a body that keeps in touch with various parts of industry. It is addressed by members of the Works Management Association and similar bodies and also by members of Trades Unions. Thus the importance of being able to control men is continually stressed.

On the subject of specialization, the students realize that complete specialization is not possible, and they have even been known to ask for a slight shortening of the courses so that a more general education can be obtained.

Finally, it is not true to say that the university forms a community out of touch with the world around. A young man at the university does not live in an artificial and sheltered atmosphere, the non-residential colleges in particular being very much in touch with local conditions.

Mr. C. F. Partridge: The majority of educational experts in this country to-day are on the side of part-time day training, and agree that part-time day training caters for all types of technical education. Since part-time day training requires attendance by the student for at least one whole day per week, it differs from all other systems of technical training in requiring the active co-operation of industry.

The mechanical engineering and building industries are supporting part-time day training in increasing numbers. The response of the electrical industry differs geographically and sectionally. From the point of view of locality, the response in Birmingham is not satisfactory. From the point of view of sections of the industry, the response appears to be greatest in the supply industry and least in the contracting industry.

Discussions of the type we have had this evening gain enormously in value if they are followed by constructive action. It is suggested, therefore, that:—

(*a*) The question of part-time day training in the electrical industry being of such importance to the nation, the industry, and the youth in the industry, and having such a weight of authority behind it, merits the closest attention of this Institution.

(*b*) A Committee of inquiry into the subject of part-time day training should be set up by this Institution, the whole subject be reviewed and suitable recommendations made.

Mr. J. A. Sumner: All of those who have to educate electrical engineers, considering education in the broader sense, experience difficulty in selecting suitable candidates, and this can only be overcome by a greater development of the system of vocational testing and examination of entrants into the electrical engineering industry. In so many cases a youth will enter the industry which is the most fashionable at a given time, and there is always a danger that he may not be fitted for the vocation which he has decided to follow, with disastrous effects in later years. The profession of electrical engineering is in this position to-day and is looked upon as being the profession that an engineer should follow.

After selection for the electrical profession by a vocation-test, and if during the training at the university greater attention is paid to the need to determine for which particular branch of the electrical industry he is likely to be fitted, it should be possible for a reasonable judgment to be made as to which branch of engineering an entrant is best suited. There should not be any attempt to specialize during the university training, which should consist only of what used to be termed the "humanities," and a very general technical experience and education which will be so broad as to provide the fundamentals for solving the normal unspecialized problems actually experienced in the industry.

Prof. W. Cramp: There are certain sound fundamental principles of education from which it is not possible to depart. Laid down by Herbert Spencer they are as follows:—

(1) Those activities which, by securing the necessities of life, directly minister to the needs of self-preservation.

(2) Those activities which are involved in the maintenance of proper social and political relations.

(3) Those activities which fill up the leisure part of life, devoted to the gratification of tastes and feelings.

The higher education in a university ought to be able to cover these three branches. At the present time, modern higher education tends to produce a finished and specialized animal, instead of a well-informed and broad-minded man. It aims at producing a sort of industrial bee instead of a rational being; a creature who, under given circumstances, is guaranteed to do what is wanted, but who, when the circumstances become strange, cannot be relied upon. The aims of this higher education become more complex every year, and so the period of training for a specialist becomes longer and longer. It is no more possible to produce a specialist in engineering at the age of 21 than it is possible to produce a specialist in the medical profession. To aim at such specialization is useless, and yet it is that aim which has led to the university curricula being so overcrowded as to exclude the other two activities of Herbert Spencer's essay.

The abandonment of specialization thus appears to be the first essential. Fundamental principles properly taught at the university would include little more than is covered by the title "applied physics." The industrialists can then add a top-dressing of specialization.

If this is agreed upon, time can be found for the other two activities. The university union is the place where these can be encouraged. In this direction, Oxford and Cambridge have distinct advantages arising from the fact that the colleges are residential. Residential universities cannot be provided *ad infinitum*, and expense would bar many students from making use of them. The residential university, too, suffers from the defect that life within its walls is not sufficiently representative of the life of the outside world.

And here a word may be added about the types of student now needed. Speaking electrically, it is the men with the highest possible "self-capacitance" that are wanted, and they should be given the highest possible coefficient of self-instruction!

This still leaves much to be said about those activities which fill up the leisure part of life. A university degree should be a guarantee that a certain life has been creditably lived, not that certain academic tests have been passed. This hall-mark cannot be given by a technical college or by an external degree. My conclusions are therefore:—

(1) All universities should provide facilities for Spencer's three sections.

(2) To make this possible, the training appropriate to the first section must be made wider and more general.

(3) In the modern universities more amenities must be found for the second and third sections, and their use encouraged.

(4) Far more care must be taken in the selection of the principal and staff of such schools; and there should be freer intercourse between staff and students.

THE REPLIES OF PROF. FORTESCUE, COL. FRASER, AND MR. CLOUGH, TO THE DISCUSSIONS

Professor C. L. Fortescue: Space makes it impossible to reply to individual contributions to the discussions and compels me to deal only with the more controversial matters.

Co-operation between Colleges and Industry.

The wide recognition of the need for co-operation and the fact—clearly brought out by many speakers—that industry is recognizing this need to a growing extent, is very gratifying. Dr. Fleming's own work is well known and there are many other firms who accept the fact that satisfactory recruits for their own responsible staff can only be forthcoming if adequate attention is paid to their training. In too many cases, however, the details of the training, the supervision of the apprentices during their training period, and even the initial selection of the apprentices, lack the personal interest of the responsible managers of the concern. The judgment of an apprentice's qualities is too often left to members of the works staff who are already more than fully occupied with their normal duties, and often that judgment is unreliable.

Dr. Fleming advocates in this discussion—as he has done elsewhere—the inclusion of practising engineers on the teaching staff of the colleges and even the undertaking within the works themselves of much of the instruction now given in the colleges. To a certain extent this proposal is already being put into practice, for many part-time members of the staffs of technical colleges are engaged in local industry and have proved good teachers. A few of them occupy high and responsible positions in industry, but the fact that these are not numerous is an indication of the real difficulty in Dr. Fleming's plan. Teaching—even of a technical subject—is an art requiring time and concentration, and it is not to be expected that many men carrying heavy responsibilities in industry can give the necessary effort to become real teachers. But, as so many speakers pointed out, it is a rapidly changing world, and Dr. Fleming's plans may even quite shortly be put into operation more extensively. No thoughtful teacher of engineering science will regret such a development.

Sandwich systems also call for co-operation, but of a rather different kind. The "Box and Cox" plan described by Dr. Ashton is ingenious and provided the apprentices are properly chosen and the maintenance grants are duly provided by long-suffering ratepayers, the scheme should work admirably. It will certainly be watched with interest!

Personal Characteristics.

There is a general insistence on the need for young men of the highest character in the engineering profession, but few of those speaking most glibly on this subject took the trouble to define exactly what they meant by character. It would be very instructive if some of the speakers who made a great point of personal qualities could be persuaded to write down a list of their acquaintances whom they consider to have the necessary qualities; and having done that, to enumerate the particular qualities to which they attach importance and then to examine point by point the qualities of their acquaintances whose names are in the list. The results would be surprising. Moreover, this experiment would bring home to them that it is only the oldest of their acquaintances that they can evaluate with any degree of certainty—a fact pointing to the impossibility of forming a sound judgment of personal qualities in the course of a short interview.

The needs of engineering in this respect are the same as those of all professions, and the only relevant question is the extent to which an engineer's education exercises an exceptional influence. Several speakers disagree with the statement in my opening paper that the training after the age of 16 had little effect on intrinsic personal qualities. It is, of course, true that if two otherwise equal boys are brought up under entirely different conditions the results will be superficially greatly different. But if the opportunities are not greatly different—as, for example, with university and technical college students—there is little reason to expect that the ultimate results will be greatly different. Similarly, given approximately equal opportunities, a really able boy will prove himself a better man than a boy of limited ability, even though such differences in training as there may be are in favour of the latter.

The Influence of the University.

This influence has been stressed by Prof. Cramp, and his views are generally accepted. But there are one or two dissentient notes and, under the conditions now prevailing, there is much less difference between the university and an industrial organization than is commonly assumed. Every large organization has its clubs and its sports grounds. The representatives of the large industrial concerns compete in sports of the highest standards, and recruits of the industry can, if they have it in them, take their part in all social activities alongside men who are daily wrestling with the realities of life. As one speaker remarks, contacts of this kind may well have advantages over those of the more rarefied atmosphere of the university. Be that as it may, however, it is undoubtedly true that the universities are not the only centres of intellectual activity nowadays and that a boy debarred from entering a university is not thereby wholly cut off from intellectual life!

The Functions of the University and the Technical Institution in Engineering Education.

Many speakers appear to lean towards the policy of confining all technical training to the technical institutes and the works; leaving to the universities courses in the "humanities" and in general scientific theory. The enormous development of the local technical colleges throughout the country in the last two decades is a new factor in our national scheme of education, and is a factor definitely favouring this proposed policy in all branches of applied science—even including the biological sciences.

Dr. Chapman suggests that the university courses should come after 4 years of works plus technical college training. This seems to be putting the cart before the horse, since the university courses should constitute the foundation on which technical training should build.

One year in works after school, followed by a university course of 3 years is common nowadays and is advocated by many speakers. But it is not wholly successful, in that it does not provide the very desirable gradual transition from school conditions to the complete freedom of the works. Even where part-time attendance at a technical college is compulsory throughout this year, few boys who have done only one year or even less after the School Certificate gain anything of value from works experience other than a type of training appropriate only to a trade apprentice. Close supervision is essential with young boys of this kind, and if they are also to spend a good deal of their time under conditions similar to those of a school, why not let them remain at school and have all the advantages of 2 full years after the School Certificate stage? If the schools do their duty, such boys will be far better educated men in the end.

What then are the relative functions of the university and the technical college? In so far as the higher-grade personnel of the industry is concerned, these discussions have produced expressions of opinion largely cancelling one another and to that extent have failed to answer this question. This failure is, perhaps, one of the strongest arguments for Dr. Chapman's proposal that some form of Education Group should be started within The Institution to consider such questions. Is it possible that the Education and Examinations Committee of the Council should be charged with the duty of investigating such questions, reporting upon them and on occasions initiating discussions of a formal or informal nature? Many speakers make urgent appeals for a full discussion of the training of the trade apprentices who are destined to become the skilled manual workers of the electrical industry. This is, perhaps, another matter for the deliberations of the Education Committee.

Specialization.

Many speakers decry specialization in the course of the theoretical training, on the ground that it is antagonistic to an adequate training in what they describe as the fundamentals; and in most cases their remarks are directed against the proposals for limitation of the range of engineering practice advocated in my opening paper. As to whether this criticism is justified or not is a question of the meaning of the terms used. In my opening paper I did not use the word "specialization," owing to the loose way in which it is employed in this connection. I advocated—as I always have done—a limitation of the subject matter of current engineering practice for three reasons, viz:—

(*a*) That by doing so, more time can be devoted to the essential theoretical work;

(*b*) That the limited range of subject can be dealt with much more thoroughly than is possible if the whole range of electrical engineering practice is included; and finally

(*c*) That it is the function of the practical training to give the young engineer the full knowledge of the practice of his own branch which is essential before he can undertake responsible work.

If it is this policy which is criticized, I am wholly unable to accept the criticisms, for they are illogical. Dr. Paterson says that he prefers young men trained as physicists, since they can more easily learn their engineering afterwards than a man trained in engineering can learn his physics. This leads to the conclusion that the ideal course of theoretical training would be one confined wholly to mathematical physics. Many very distinguished men have had such a training, but it is not suitable for the majority of engineering students. The very fact that they have joined the engineering departments shows a temperament to which purely theoretical work makes little appeal. For them, some branch of engineering practice must be chosen as the vehicle for the theoretical principles. What I propose is that the range of subjects chosen should be limited and should be the ones in which the student is most keenly interested. As Prof. Marchant points out, this is in nearly all cases the branch that the students follow in their professional careers. A few change their branch; but this does not alter the argument since, if the young engineer can apply his basic knowledge in one branch, he can also apply it in another if he is given a reasonable opportunity of looking into the prevailing conditions.

I disagree entirely with Prof. Cramp in this matter. He advocates a course of training which involves the application of electrical principles to all branches of electrical engineering and a good deal of mechanical engineering. This entails an additional year at the college and for the majority of the students it gives them no advantage; for most of them do, in fact, know beforehand the branch they are to enter, and in that branch they are not better trained—if as well—as a student who has followed the course I advocate. Prof. Cramp is thus sacrificing a valuable year of the majority of his students for the questionable benefit of a few who are doubtful with respect to their futures or who have no special interest. I can neither agree with Prof. Cramp's policy in this respect nor accept the arguments of those speakers who suggest that students must have a knowledge of all branches of engineering in order to be able to take any job that may be forthcoming. This latter argument appears to me to betray an inferiority complex which bodes ill for these speakers' own futures and is certainly not an outlook to be encouraged in students.

Experience of post-graduate courses of training also has a bearing on this question. There is universal approval of these courses from those who have watched the intellectual improvement of students taking them. Here, the range of subject is reduced to a single problem and yet it is found that for a young engineer with a flair for development work it is an excellent and valuable training. It is a thorough preparation for similar work in other subjects, because it is an experience of bringing to bear on a single problem all the results of the previous training. That power, I submit, is the real function of any form of academic training, and if this is pilloried as "specialization," then I remain entirely in favour of it on the grounds that it is the only reasonable policy and that it is in fact the policy that has been followed in all branches of teaching since mediaeval times.

The Evening-Class Student.

Many speakers put in a plea for the consideration of the evening student and for the improvement of his working conditions. Many Corporate Members of The Institution enter by this avenue and, in so far as they are concerned, the question is relevant to the present discussion.

There is a concensus of opinion that the present plans impose too great a mental and physical strain on the majority. Moreover, it is not in the interests of the community as a whole that all the young workers should be given a high theoretical training as well as practical manual training. The problem thus reduces to a question of picking the right candidates and giving them ample facilities. They will be few in number because the most promising boys of the elementary schools have already had the opportunity of passing on to the secondary schools. But having been found worthy after, say, 2 years in works, this small number should be treated generously. Dr. Ashton's scheme is by no means too generous. It should be possible also for the same scheme to be used even where there is no local technical college, for the small number of picked apprentices would be worthy of sufficiently large maintenance grants for them to leave their homes and live near larger colleges in other centres of population. Such a policy might well prove an economy in so far as the community as a whole is concerned, for it might reduce the multiplication of colleges and equipment.

For the remainder of the young workers, some evening work is no doubt desirable; but it might be of a very general nature and possible not scientific or technical until quite the late stages are reached.

Conclusion.

The engineering profession is in direct competition with the other professions for the best of the younger generation. The extent to which it is successful in this competition is in the main a question of the rewards it can offer; rewards in the form of responsibility, of opportunity for new development, and the chances of making great contributions to the advancement of civilization; rewards not wholly financial but, nevertheless, adequate in this respect. If these rewards are inadequate, if there is any tendency for the young engineer to be unduly restricted, the right men will not be attracted. No system of training can influence this situation and the standard of its personnel is thus primarily a matter of the industry itself.

Col. H. Cecil Fraser (*in reply*): The discussion has shown a fairly general appreciation of the desirability of an improvement in the training of character. Mr. Gill inquired, in a rather different connection, whether it was not possible to make industry rather more articulate as regards the type of training which it prefers. It has been my object to make plain the type of recruit which industry prefers, and I would emphasize that it is the educationist rather than the employer who must be responsible for producing such a type. The somewhat petulant attitude exemplified by Prof. Kapp seems to deserve an answer in this connection. No one suggests as a panacea for present evil the lowering of the standard of degree examinations coupled with an increased insistence on physical training. What is required is a very much more broadminded tackling of the general problem of character-making.

I have been accused by Prof. Cramp of contradicting myself in one respect, and I must plead guilty to the charge of not making my meaning entirely clear. When I said that failure in examinations is often due to unwillingness to work at uncongenial subjects, I had no intention of minimizing the value of steady application. But it is possible at present for a pupil to gain, it may be, four Credits in the School Certificate, and fail to be awarded his certificate because he does not pass in one subject which is placed in another group. I am confident that the right tactics in education are those of the " soft spot," of allowing the pupil to advance in those directions which he finds most attractive. To hold him back by an insistence on the rigid attainment minimum of an arbitrarily fixed standard is merely to stifle what original keenness he may possess, and perhaps to deprive him of at least a full year's educational progress.

Prof. Cramp also objects that technical knowledge acquired in later life is liable to be superficial and lacking in conviction. I would agree with him, to the extent of admitting the vital importance of a grip on fundamentals, especially in the case of a practical science such as electrical engineering, whose first principles are firmly based and empirically verifiable. But my conviction that technical detail can be acquired in later life remains unshaken. In this connection I would recall a certain famous rowing coach who was wont to say " Give me a man of the right build and I will make him a Blue." So, speaking as an employer, I would say " Give me a man of the right type and I will make him an engineer."

I am only too well aware that, as Mr. Everett says, the problem has an important economic aspect. Yet I believe the gap between the elementary, secondary, and technical college education on the one hand, and expensive boarding-school and university training on the other, is capable of being narrowed, and that this narrowing is one of the main problems which the present-day educationist is called on to solve.

Mr. F. H. Clough (*in reply*): I feel gratified that the brief opening remarks have expanded into a wide and comprehensive discussion to which many eminent educationalists and engineers have contributed. Anyone interested in technical education will find much of value and interest in this discussion after he has done a certain amount of winnowing to extract the grain.

In my opening remarks I emphasized the importance of fundamental knowledge and also of co-operation between industry and education. I made a plea for as much cultural, as distinct from technical, education as time would allow; and associated this with the inclusion of a foreign language. I am pleased to feel that in this wide discussion there has not been much disagreement with the ideals which I expressed.

THE SURGE PROTECTION OF POWER TRANSFORMERS

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SUMMARY

The paper commences by reviewing the methods adopted for the protection of overhead lines and transformers from the incidence of lightning. It is then pointed out that in many cases it is not economic, and in others technically difficult, to provide sufficient line protection, so that transformers connected to such lines are likely to be subjected to transients having high voltage-amplitudes and high time-rates of voltage change.

The question of transformer winding breakdown due to transients is then reviewed and evidence is brought forward to show that the important stresses are those between coils and turns and not those in the major insulation. The conclusion drawn is that transformers can advantageously be protected in most cases by those wave-flatteners which, under all conditions, permit only safe rates of voltage-change to exist at the terminals.

Three representative wave-flatteners—condensers, inductance coils, and surge absorbers—are then discussed and equations are given which indicate the manner in which their performances are calculated, consideration being given to all degrees of lightning conditions, including those which cause flashover near the protected transformer.

Then follows an experimental analysis of the axial stresses, and their reduction by the use of wave-flatteners, in various transformer windings under travelling-wave, travelling-wave flashover, and direct lightning-stroke conditions. Several transformers, differing in rating, mode of winding, natural frequency, and value of α, are employed. The results are presented in the form of gradient-distribution curves so that the relative performances, under various conditions, of the three kinds of flattener may be readily examined and the effects of changes in transformer constants compared.

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(1) LIST OF SYMBOLS

C_g = earth capacitance of a transformer winding.
C_s = series capacitance of a transformer winding.
$\alpha = \sqrt{(C_g/C_s)}$
t = time.
$p = \partial/\partial t$.

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[*] Ferranti Ltd., Hollinwood.

[†] Ferranti Electric Ltd., Toronto.

LIST OF SYMBOLS—*continued*

a, b = parameters in the equation $E(\epsilon^{-at} - \epsilon^{-bt})$.
E = crest voltage of incident waves.
e_2 = output voltages of inductances or surge absorbers, or voltages across condensers.
Z_1 = surge impedance of incoming lines.
C_e = effective capacitance of transformers.
C_1 = capacitance of condensers or capacitance of surge absorbers.
$C = C_1 + C_e$.
L = inductance of inductance coils.
L_1, L_2 = inductances of the primary and secondary windings of surge absorbers respectively.
R_1, R_2 = surge resistances of the primary and secondary windings of surge absorbers respectively.
L_e = effective inductance of surge absorbers $= L_1 - M^2/L_2$.
R_e = effective resistance of surge absorbers $= R_1 + M^2R_2/L_2^2$.
M = mutual inductance between L_1 and L_2.
$S = 1 - M^2/(L_1L_2)$.

(2) INTRODUCTION

Considerable inconvenience and expense has been occasioned on many overhead transmission systems by breakdown of apparatus and discontinuity of service due to lightning causes, and as a result numerous auxiliary devices have been developed to reduce such troubles to a minimum. The important ones may be classified thus: (*a*) earth wires, (*b*) Petersen coils, (*c*) de-ion gaps, (*d*) substation shielding, (*e*) arresters, (*f*) co-ordinating gaps, (*g*) non-resonating transformer designs, (*h*) wave-flatteners. Each may be employed separately or in conjunction with one or more of the others. Many of them are not specifically used for the protection of the transformer windings but rather for the purpose of reducing line outages. Nevertheless, most of them do serve the former purpose to a greater or less extent. They will be discussed briefly.

(a) Earth Wires.

An earth wire mounted above the line conductors reduces the surge voltage impressed thereon by induction[*] (important on the lower-voltage lines), acts as a shield to prevent the connection of lightning strokes with the conductors, and reduces the risk of flashover from a tower to a line conductor.[†] They are installed generally for the prime purpose of preventing outages and not as a transformer protection.

Their effectiveness as shields, however, is dependent on there being very low resistances in the earth connections at the tower feet, and in practice it has been found that unless these resistances are maintained below a figure of the order of 10 ohms flashover will be prone to occur from a tower to a line conductor.[‡] The connected transformers will then be subjected to surges of a severity for a given line depending on the distance between the point of flashover and the transformers. Naturally this distance will often be short enough to make these surges dangerous to the transformers.

In terrains where it is impossible to obtain the required low value of the earth resistance directly the counterpoise[*] can be employed for this purpose. It is, however, very expensive and so far its use has been limited to important 220-kV, 132-kV, and 66-kV lines. To a lesser extent the same remark regarding expense applies to the earth wire, so that it is often not economically practicable to provide secondary distribution systems with these devices.

(b) Petersen Coils.

A Petersen coil[†] connected between the system neutral and earth clears a line-to-earth fault by virtue of the fact that it carries a lagging current equal in magnitude and opposite in phase to the charging current at the fault. While of recent years they have come into prominence, the purpose of these coils is simply to prevent the type of outage mentioned and not to afford transformer transient protection.

(c) De-ion Gaps.

These gaps, which are connected across the insulator strings, have the property of preventing the formation of a maintained power-frequency arc when a transient flashover has occurred.[‡] Their main purpose, like that of the Petersen coil, is therefore to prevent circuit-breaker operation and thus to maintain continuity of service. So far as the authors are aware they have only so far been employed with a setting just low enough to rob the insulators of the flashover, and thus from the point of view of transient over-voltages the position is nearly the same as if the gaps were not in use. They thus afford no protection to connected transformers.

(d) Substation Shielding.

To prevent lightning strokes connecting with apparatus either directly, or indirectly via insulator flashover, several interconnected earth wires are sometimes mounted above large substations and run out for a short distance along the lines, and, in general, such an arrangement is satisfactory.[§] This measure of protection results not only from it being a reasonable proposition to maintain low values of the earth resistance locally at the station, but also from the fact that a large number of interconnected overhead earth wires can together reduce the earth-wire system surge impedance to a value sufficiently low to prevent the tower-top voltage rising to flashover value. Nevertheless, an earth resistance of a few ohms only may be great enough to cause flashover with strokes of great current magnitude, with an application of a surge to the transformers as a consequence, and thus trouble, particularly on medium-voltage stations, still persists.[||] Large numbers of stations are only incompletely shielded, or are not shielded at all, and in such cases direct strokes may of course connect directly with the conductors near or at the transformers. This applies particularly to small rural transformer stations.

(e) Arresters.

Arresters are used to protect the apparatus connected to the line by reducing the surge-voltage amplitude to a low value rather than to protect the line itself.[¶] At present the installation requirements of these devices are such that they must be shielded from direct strokes and must be connected to low-resistance earths.

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[*] See Bibliography, (1).
[†] *Ibid.*, (2).
[‡] *Ibid.*, (3) and (4).

[*] See Bibliography, (5).
[†] *Ibid.*, (6) and (7).
[‡] *Ibid.*, (8) and (9).
[§] *Ibid.*, (10).
[||] *Ibid.*, (11).
[¶] *Ibid.*, (12).

Thus, so far as large stations are concerned they are generally employed in conjunction with (*a*) and (*d*), and in cases where a complete earth-wire network is not employed at least an earth-wire system stretching out for a few spans is necessary.* Nevertheless, as pointed out in Section (*d*), there is the risk of strokes connecting with the conductors via insulator flashover even when shielding is employed, and in such cases the lightning current in point is not limited by the line surge impedance. Thus from the point of magnitude of surge current and of rate of voltage-rise, conditions more onerous than those caused by travelling waves are likely to obtain at the arrester and transformer terminals.

So far as the smaller and isolated substations operating at the lower voltages are concerned, the position is worse since it is often difficult to provide low values of the earth resistance and generally no shielding is economically possible.

It will be seen, therefore, that there may be some difficulty in obtaining the conditions necessary for the correct functioning of arresters, and that there are considerable limitations to their installation.

(f) Co-ordinating Gaps.

Rod co-ordinating gaps† are used in an effort to limit to safe amplitudes the over-voltages reaching transformers, and are employed either as the only means of defence or in conjunction with (*a*) and (*d*). It will be evident later that the resulting impulses are still dangerous to transformer insulation, but for the moment another limitation will be discussed. This limitation results from the large impulse ratio which a rod-gap exhibits under the influence of steep-fronted waves or direct strokes, and on which account it has been found desirable in practice to reduce the gap settings below the nominal co-ordinating values in order to restrict the amplitude of such over-voltages to a safe value. This has, of course, the effect of correspondingly lowering the flashover voltage of the gap for less steep transients so that smaller-amplitude slow-fronted travelling waves provoke frequent and unnecessary flashover.

(g) Non-resonating Transformer Designs.

The non-resonating transformer‡ is one which is designed to have an initial voltage distribution equal to the final distribution. As a consequence the axial voltages in the winding are uniformly distributed (the more important characteristic) and the voltages to earth never exceed those obtaining at the initial distribution. The effect is achieved by using capacitance shields, usually at line potential, insulated from the tank and the winding.

(h) Wave-flatteners.

The wave-flatteners§ in common use to-day are surge absorbers, inductance coils, and condensers, the first two being connected in series with the line and the transformer, and the last in shunt with the transformer. Their object is to flatten the fronts and tails of transients to an extent such that the axial gradients in the protected winding are reduced to a safe level.

(j) Summary and General Remarks.

Devices (*a*) to (*f*) aim essentially at limiting the number and magnitudes of the surges arriving at the transformer and, as will be evident, in general their effectiveness is not complete but depends partly on conditions and partly on the allowable expenditure.

Thus, in a large number of cases, the connected transformers will, despite their installation either singly or severally, be frequently subjected to surges having amplitudes of the order of the transformer terminal flashover voltage, and the fronts and tails of these surges will be as steep as if the protective devices were absent. Therefore in order to gain immunity from transformer breakdown it is often necessary to aim for a surge-proof transformer, that is to employ a special non-resonating design, or to limit the rates of voltage-change at the transformer terminals by incorporating wave-flatteners. For the reasons given later, the choice of flattener is confined to surge absorbers, condensers being unsuitable for flashover or direct-stroke conditions and inductances for travelling-wave conditions.

In cases where no external line protection is employed (and this is frequently the case on many systems), the connected transformers have to withstand a relatively greater number of surges so that without the further safeguard the risk of breakdown is greatly increased.

(3) CHARACTERISTICS OF TRANSFORMER STRESSES

The statement that practical immunity from lightning breakdown is to be obtained by the use of devices (*g*) and (*h*) now needs amplification. To do this it is necessary to discuss briefly the mode of breakdown of a transformer winding, leading to a discussion of the relative importance of failures of the major insulation between high- and low-voltage windings and between windings and earth, and failures of the interturn and intercoil insulation, and also the nature of the internal stresses and the methods of controlling them.

(a) Internal Voltages and the Mode of Breakdown.

The normal failure across the major insulation is due essentially to the amplitude of the surge, the wave-shape only affecting matters in so far as the insulation will have a greater impulse ratio when the wave-front of the surge is steep. When such a breakdown occurs it is easily recognizable. It shows up generally as a puncture of the high-to-low insulation, as a flashover between a lead and the tank or cover, or as creepage from the end of a coil stack to earth or to the low-voltage winding.

The normal failure due to the time-rate of change of voltage at the terminal is also readily recognizable as pin-holes or charring between turns or between sections. In such cases the amplitude of the surge does not affect matters directly. For a fixed wave-shape increasing the amplitude by a given factor increases the gradients by the same factor simply because the time-rate of voltage change is also correspondingly increased.

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* See Bibliography, (13).

† *Ibid.*, (14).

‡ *Ibid.*, (15), (16), (17).

§ *Ibid.*, (18), (19), (20), (21).

There is another type of failure, however, caused by the axial stress along the coil stack, which is sometimes incorrectly classified as a major insulation failure. When two adjacent coil sections are so connected that the surge voltage occurs between their inside ends, an electrostatic stress in the adjacent inner insulating cylinder will be produced which will have a large component in the axial direction. If this stress exceeds the electric strength of the insulation in this direction the cylinder will be damaged in the axial direction. Later, if the stress is great enough the axial failure will be extended through the cylinder and will lead to a breakdown between the high- and low-tension windings which on a casual examination might be classified primarily as a major insulation failure. The fact remains, however, that the axial stress was the primary cause of the trouble.

Failures of all three kinds may and do occur in practice, but operating experience and full-scale experiments show that by far the greater number of failures take place between coils[*] and between turns.[†]

In fact it is the relative weakness of transformer windings in the axial direction that originated the practice of reinforcement at the line ends and at other critical points such as tapping sections, and that to-day justifies the stringent 50-cycle tests that are called for on " between turns " samples in most standard specifications.

The physical reason for the state of affairs just explained is not far to seek.

Although standard specifications stipulate conductor insulation which corresponds to power-frequency gradients between consecutive turns very much more conservative than those which are usual in the major insulation, nevertheless the grouping of conductors in sections entails that two conductors, although electrically separated by several turns, may be nearly adjacent, with the result that a single thickness of conductor insulation will here carry several times the nominal voltage per turn. In this way the actual maximum working gradients across inter-conductor insulation may reach or exceed the order of those in the major insulation.

Now, with regard to the major insulation stress under transient conditions, measurement of the internal voltages to earth in transformer windings shows that throughout the windings the voltages across the major insulation never exceed by more than a few per cent the amplitude at the end of the windings, that is at the terminal.[‡] Actually, for voltages having durations of less than 20 microseconds—and the greatest-amplitude ones are usually much less than this—the amplitude of voltage across the major insulation is probably everywhere less than at the terminal. Thus the actual stresses are increased approximately only in the ratio of the terminal impulse flashover voltage to the crest value of the operating voltage.

If the transient axial voltages were uniformly distributed in a winding, the axial gradients would be increased in the same ratio. Actually, however, under abrupt transients the worst axial gradients are additionally increased by the factor α which may range from 5 to 30, depending upon the transformer design.

While the impulse breakdown strength of axial insulation is certainly greater than that of the major insulation, as a net result most generally a transformer is considerably weaker to impulses in the axial insulation than in the major insulation, and for this reason the bulk of transformer failures occur axially. The fact that over a long period of years the standard 50-cycle pressure test has been looked upon by operating engineers and consultants as a sufficient test for the major insulation, while additional tests are called for on samples of between-turn insulation, would in itself be some justification for believing that the major insulation is amply strong in practice.

(b) Control of Axial Stresses.

The excessive voltages in the axial direction are due to the combined effects of the time-rate of applied voltage-change and the non-linearity of the initial voltage distribution in the winding, whose form is controlled by C_g and C_s. The more this distribution departs from linearity, that is the greater the value of α or $\sqrt{(C_g/C_s)}$, for a given terminal voltage the greater are the axial voltages.[*] Minimum voltages must be obtained by small values of α or by the artificial minimization of the rates of voltage-change at the terminal.

The constant α could be reduced by increasing C_s or decreasing C_g. The capacitance C_s would be increased by using coils with a deep radial build or by connecting condensers between sections. With regard to the former, as a rule the designer is limited in his proportions and such coils increase the cost or the reactance, or both. If condensers are used they are costly and space must be found in the transformer tank for mounting and insulating them. In addition, they do not strike directly at the suppression of local oscillations inside the sections. The capacitance C_g would be decreased by increasing the clearance between the high- and low-tension windings,

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[*] See Bibliography, (22), (23).

[†] This is the experience of the authors and many others. In 1915 Weed [see Bibliography, (24)], for instance, made the statement "From the first use of transformers the occurrence of excessive voltages between turns or sections . . . forced itself on our attention by its results in punctured insulation." More recently Putnam [*ibid.*, (25)] stated "An ordinary transformer of either core or shell construction, when tested to destruction with surge voltages, will usually fail lengthwise of the high-voltage stack."

[‡] See Bibliography (10).

The authors have noted that there is often some measure of disagreement between theory and measurement in regard to the voltages to earth inside a transformer winding and in regard to the harmonic frequency relations. Investigations have shown that this may be due to the generally accepted assumption of a linearly graded mutual inductance [see Bibliography, (17)] between parts of the winding not always being admissible.

Actually it has been found that in some windings the mutual inductance decreased very rapidly with distance; thus in the equation below (which is one of the simultaneous equations required for the determination of the internal voltages and which gives the relationship between the voltage and current in a section of the winding when taking into account the effect of the currents in other parts of the winding)

$$\frac{\delta e}{\delta x} = i_2 r + L\frac{\delta i_2}{\delta t} + \sum M(x, y) \cdot \frac{\delta i_2(y)}{\delta t} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

there is

$$\sum M(x, y) = \frac{M}{1-\varepsilon^{-m}}\left\{2-\varepsilon^{-m(x-1)}-\varepsilon^{-m(l-x)}\right\}$$

for a coupling varying inversely as the exponential of the distance, where L and r=self-inductance and resistance of a coil section respectively, M=mutual inductance between one section and the next, x and y are points in the winding measured from the neutral, and i_2 and $i_2(y)$ are respectively the currents in the xth and yth sections.

For couplings varying inversely as the distance and inversely as the square of the distance these are respectively $\Sigma M(x, y) < M\left\{\log_e x + \log_e (l - x + 1)\right\}$ and $\Sigma M(x, y) < M(\pi^2/3)$.

When such expressions for $\Sigma M(x, y)$ are incorporated in (1) the discrepancies referred to at the beginning of this footnote are considerably reduced.

[*] For views on transformer transient theory see, for instance, Bibliography (10), (17), (26), (27), (28).

but this space is limited by the maximum allowable leakage reactance and the size.

In effect a reduction in α is also obtained by the use of a shield at line potential. Essentially this is the principle of the conventional non-resonating transformer and enables a practical design to be produced. It does not appear, however, to be economical for the smaller ratings and the lower voltages unless only partial shielding is resorted to. Non-resonating transformers will not be discussed further in this paper.

It will now be evident that apart from shielding it is usually impossible for the designer so to proportion his winding that a low value of α is obtained at will. It should be realized, however, that even the more uniform initial distribution resulting from a small value of α, while giving a reduction in the surge " volts per coil," owing to the existence of other factors does not necessarily cause a corresponding reduction in the " volts per inch " in the insulation between coils. In fact, two transformers described later having the same voltage and current rating had values of α in the ratio of 3 : 1, yet the maximum " volts per inch " in the transformer with the smaller value of α was only about 20 % less than that in the other transformer.

It would thus appear that to minimize the rates of terminal voltage-change by means of wave-flatteners is preferable as a means of reducing the axial gradient, since, as will be evident later, this always gives a positive reduction in the " volts per inch." In addition, since flatteners are external to the transformers there is no added restriction to the design of the latter, and they have the great advantage that they may be added to existing transformers.

(c) Permissible Rates of Surge Voltage-change at a Transformer Terminal.

The problem now arises as to the allowable rate of terminal voltage-change to enable a transformer to withstand severe surges. In considering the problem the maximum axial stresses that can arise have to be taken into account, and then the degree to which these stresses should be reduced to make the transformer capable of withstanding these surges without breakdown has to be decided. Since transformers at present vary a great deal in the values of their unprotected axial strengths, conservative figures should be taken and the experience gained when put into practice must be such as to show a good record of operating performance.

As a result of analysis of this nature, together with an examination of present-day practice in transformer design, it has been found that if the wave-front or tail at the terminal is not less than 3 to 5 microseconds, the maximum axial winding gradient is nowhere greater than one-third or so of that which would arise under the worst envisaged conditions. For instance, referring specifically to No. 1 transformer and the protection given by a surge absorber which flattened a 0·2-microsecond front to a 5·2-microsecond one, it is seen that under various specific terminal conditions the absorber effects improvements ranging from 2·86- to 6·7-fold. The figure indicating the overall performance is, however, the ratio of the greatest stress without an absorber to the greatest stress with the absorber, irrespective of terminal conditions, and for No. 1 transformer this ratio is 3·3.

Further, it has been found that, for the same degree of flattening, neither the overall improvement nor the 0·2/40-wave improvement varies much with the voltage or kVA rating of transformers or with their winding arrangements, and the latter is exemplified by the curves in Figs. 9, 10, 11, 38, and 39, which are drawn for the 0·2/40 wave and for absorbers giving the same degree of flattening. In the worst case the improvement with the 0·2/40 wave is only 2·5-fold, but as in the case of No. 1 transformer the overall improvement is greater than this. With a transformer of another type and an absorber giving a smaller degree of flattening the 0·2/40-wave improvement, as shown in Fig. 40, was 2·7. Further, that the amount of flattening proposed gives reasonably uniform degrees of stress production in all cases is well illustrated by the facts that for transformers Nos. 1 to 6 the respective maximum relative gradients under 0·2/40-wave conditions are 100, 76, 122, 78, 89, and 81, while the corresponding protected gradients are 35, 31, 29, 28, 35, and 30.

(4) WAVE-FLATTENERS

(a) Condensers.

The requisite amount of flattening can readily be obtained under travelling-wave conditions, where the line surge impedance limits the surge current, by the use of condensers of reasonably small capacitance connected in shunt with the transformer. This can be confirmed from the equation below,* which gives the voltage e_2 impressed on a transformer when the incident wave is $E(\epsilon^{-at} - \epsilon^{-bt})$.

$$e_2 = \frac{2E}{1 - aCZ_1}\left(\epsilon^{-at} - \epsilon^{-\frac{t}{CZ_1}}\right) - \frac{2E}{1 - bCZ_1}\left(\epsilon^{-bt} - \epsilon^{-\frac{t}{CZ_1}}\right)$$

For other reasons, however, the condenser is unsatisfactory. Thus, the most important disadvantage is that no protection is afforded when a flashover occurs at or near a condenser. This is due to the fact that after the instant of flashover an oscillation takes place round the local circuit comprising the condenser, the arc, and a conductor of length depending on the position of the flashover. Since the inductance of this local circuit is small, the frequency and hence the time-rate of voltage collapse impressed on the transformer are great; the phenomenon is illustrated in Fig. 20(*a*). As a consequence excessive axial gradients will be developed in the winding, as shown, for instance, in Fig. 20(*b*). Their discussion will, however, be continued in a later Section.

Again, a condenser requires a low value of the earth resistance. If this is not obtained an appreciable fraction of the front of the wave impressed on the transformer may, under certain circumstances, be as steep as that of the incident wave.

For these reasons, together with others discussed later, condensers do not present a satisfactory solution.

(b) Inductance Coils.

With an inductance coil of appropriate size no dangerous effects arise from a flashover on the line side unless flashover is long delayed. The reason is that the local oscillatory circuit now includes the coil, so that the frequency of the resulting oscillation and the time-rate of voltage change are low.

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* See Bibliography, (29).

Under travelling-wave conditions the voltage impressed on the transformer is*

$$2E\left[\frac{\epsilon^{-at}}{K_a} - \frac{\epsilon^{-bt}}{K_b} - \frac{2}{\psi}\sqrt{(C_eL)}\epsilon^{-\frac{Z_1t}{2L}}\right.$$
$$\left.\left\{\frac{\cos\left(\frac{\psi t}{2C_eL} - \theta_a\right)}{\sqrt{K_a}} - \frac{\cos\left(\frac{\psi t}{2C_eL} - \theta_b\right)}{\sqrt{K_b}}\right\}\right]$$

where $\psi^2 = 4LC_e - C_e^2Z_1$; $K_a = C_eLa^2 - Z_1C_ea + 1$;
$\theta_a = \text{arc tan}\,(C_eZ_1 - 2C_eLa)/\psi$.

and where K_b and θ_b are terms respectively similar to K_a and θ_a with a replaced by b.

This equation shows that there is an oscillation which permits a voltage to exist at the transformer considerably greater than that which would have occurred if the inductance coil had been absent.† This may cause a flashover at the transformer terminal as illustrated in Fig. 23, with the consequences referred to in the next Section. This precludes the use of the inductance coil as a wave-flattener unless it is provided with a damping resistance.

(c) Arrangements of Capacitance, Inductance, and Resistance.

Such a circuit is shown in Fig. 1(*a*). When properly designed, under travelling-wave conditions it does not oscillate and cause an increase of voltage at the transformer terminal, and under flashover conditions the rate of collapse of voltage there does not exceed a predetermined figure. This arrangement therefore does not suffer from any of the disadvantages of inductance coils or condensers.

The circuit also has the advantage that both for travelling-wave and flashover conditions the incorporation of C_1 enables the required flattening to be obtained with a much smaller value of inductance than would be necessary in the absence of C_1. Since the losses in the coil may be appreciable and the losses in the condenser negligible, this reduction considerably simplifies space and thermal questions. This will appear in its true perspective when it is realized that even in the present arrangement the inductances required are of the order of millihenrys and that they have to withstand the full surge voltages and, accordingly, present insulation and thermal problems similar in nature to those obtaining with transformers.

Further, the provision of the capacitance C_1 at the output end, large enough to minimize the importance of the transformer effective capacitance C_e, makes for certainty in damping and obviates difficulty when C_e is unknown. With plain inductance coils having shunt resistance the only certain way to ensure adequate damping is to over-damp. This has the disadvantage that the requisite flattening can then only be obtained by a value of inductance greater than that which would be necessary with the correct damping.

(d) Surge-Absorber Design Considerations.

The surge absorber is essentially a piece of apparatus designed in accordance with this last circuit arrangement. The damping, however, is not obtained by the direct connection of a resistance across the inductance coil but via the medium of a mutually-coupled resistive circuit. The complete arrangement is shown in Fig. 1(*b*), the reason for its use as opposed to that in Fig. 1(*a*) being partly constructional and partly economic. Its performance, of course, in practice duplicates that obtained from the circuit in Fig. 1(*a*).

The design of an absorber from the surge point of view is concerned with the obtaining, from the minimum values of inductance and capacitance, of a required amount of wave-flattening under the worst conditions. Four main factors have to be taken into consideration, namely the values of the primary inductance, the capacitance, the secondary resistance, and the mutual coupling between the primary and secondary windings.

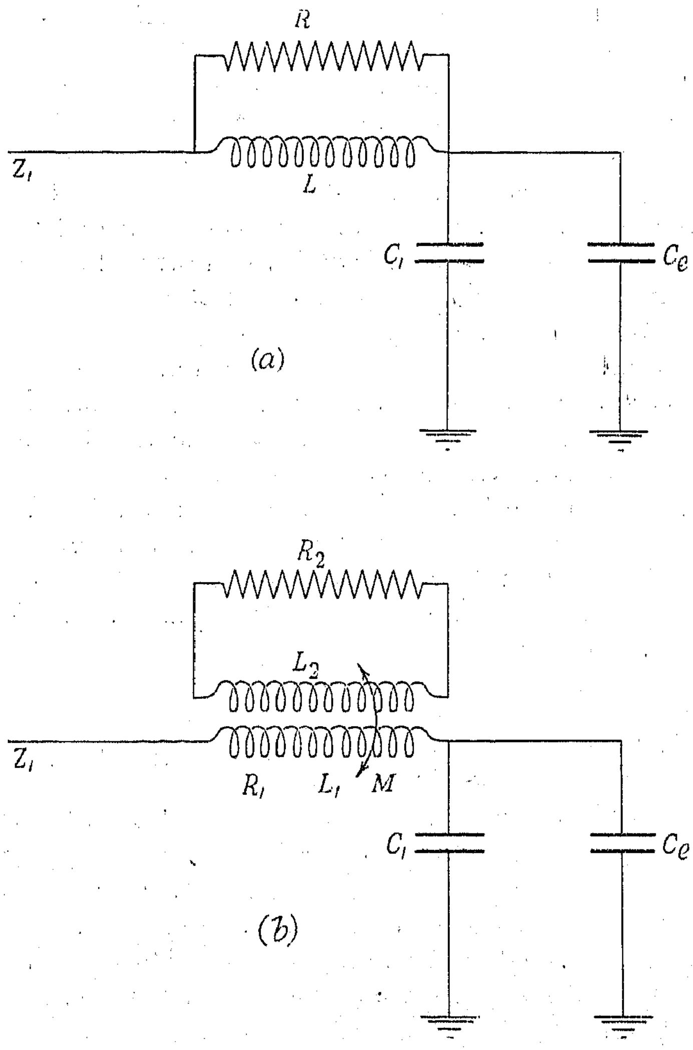

Fig. 1

With regard to the first two, the values which can be economically employed are controlled by the current and voltage ratings respectively, but in practice this sets no practical limitation to the design since for a constant value of the product of the inductance and capacitance, within wide limits the transient performance of the device can be made substantially constant. This is exemplified in the experimentally determined curve in Fig. 2, which was obtained by sending a steep-fronted long-backed travelling wave into a transformer, the latter being protected by surge absorbers having various values of L_1 and

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* See Bibliography, (29).

† *Ibid.*, (30).

C_1, both the product L_1C_1 and the damping, equal to $K\sqrt{(L_1/C_1)}$, where K is always less than unity, being maintained constant.

The effect of the coupling, the fourth controlling factor, is shown in Fig. 3. The curve therein was calculated in connection with flashover conditions ($Z_1 = 0$) from the solution of equation (1), the inductance, capacitance, and damping, being maintained constant. It will be seen that in this case decrease in coupling gives a marked increase in flattening, but with additional increase in amplitude of the output voltage.

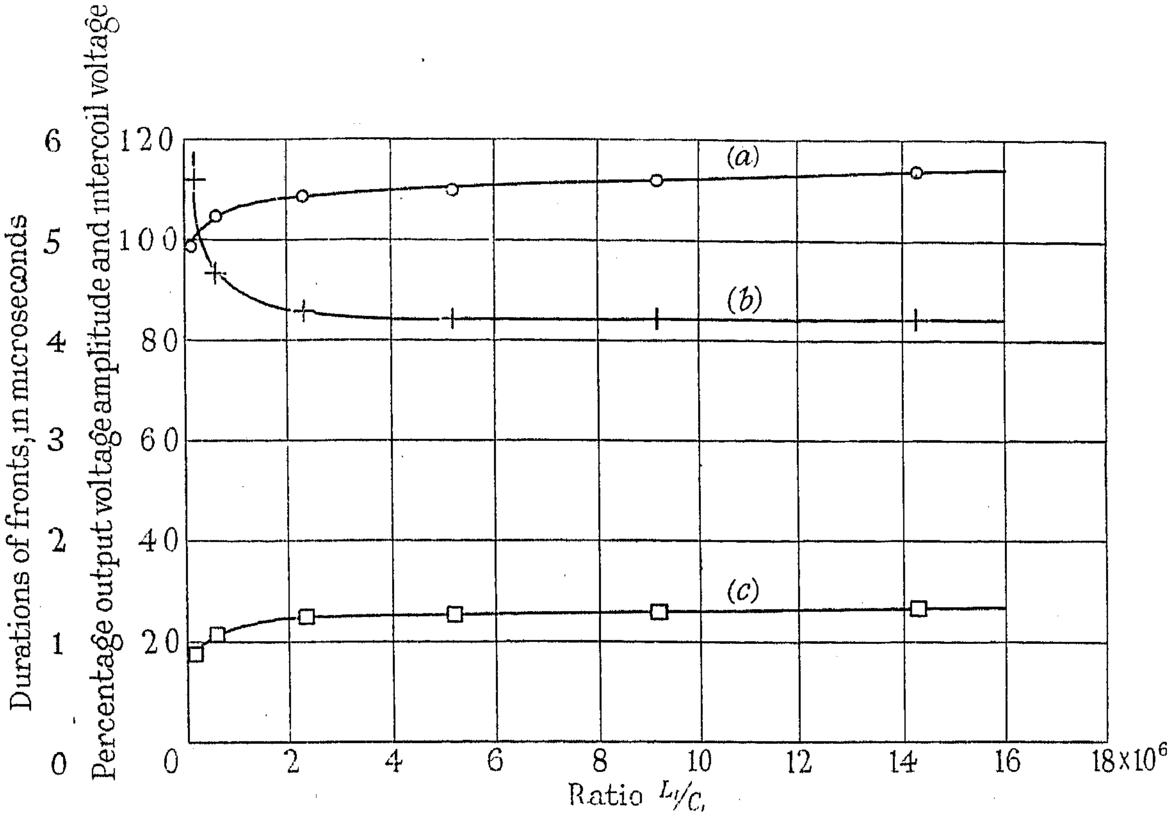

Fig. 2.—Effect of variation of ratio L_1/C_1 in surge absorbers on the amplitudes and durations of the fronts of their output waves. Constant product L_1C_1. Line surge impedance $Z_1 = 350$ ohms; 0·5/40 input waves; secondary damping $= K\sqrt{(L_1/C_1)}$, where the damping factor K is constant; constant coupling. Results obtained experimentally.

(a) Protected terminal voltage as percentage of unprotected value.
(b) Flattening, in microseconds.
(c) Intercoil voltage of a protected transformer as percentage of unprotected value.

It is seen that slightly better results are obtained with the travelling wave used when the ratio L_1/C_1 is small. This, however, does not hold under flashover conditions when the line surge impedance is absent, so that there is a lower limit of inductance below which satisfactory performance is not obtained. This is only to be expected since in the limit as $L_1/C_1 \rightarrow 0$ the device consists only of capacitance and, as pointed out earlier, a condenser is not satisfactory under flashover conditions.

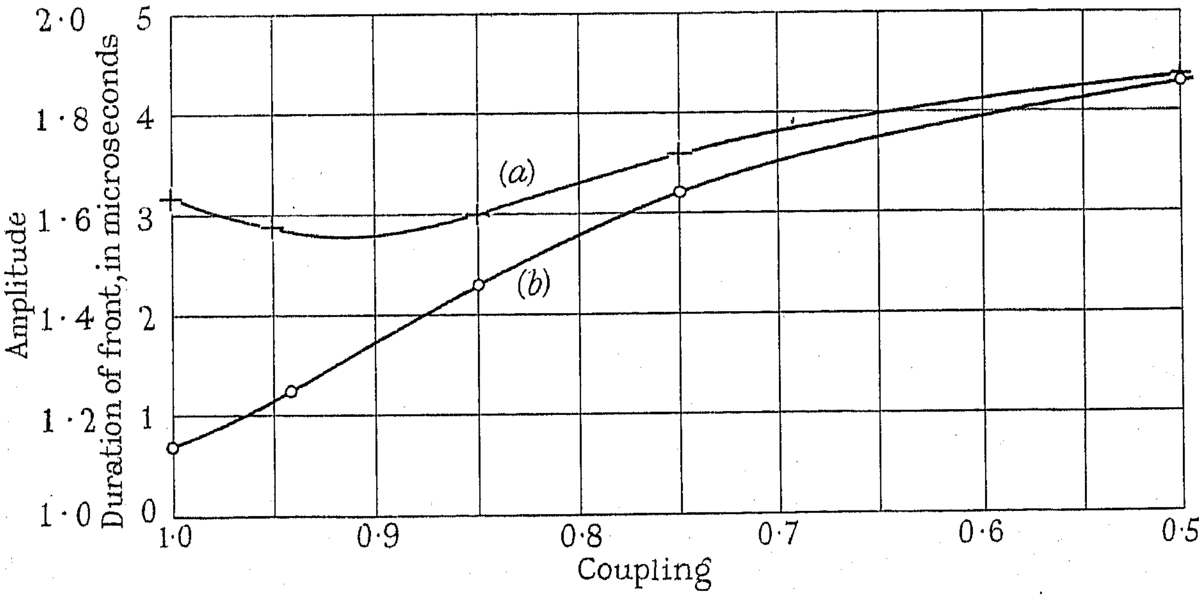

Fig. 3.—Calculated effect of the percentage coupling between surge-absorber primary and secondary windings, (a) on the durations of fronts, and (b) on the amplitudes of the output waves. Infinite rectangular incident wave, zero line surge impedance, fixed secondary damping, and fixed values of L_1 and C_1.

Under flashover conditions amplitude-increase, however, has little significance and under travelling-wave conditions, where Z_1 has finite values, the amplitude increase will be much less than that shown in Fig. 3. This is illustrated in Fig. 4, which was computed from equation (1) for two values of the coupling and for critical damping and for Z_1 equal to 350 ohms.

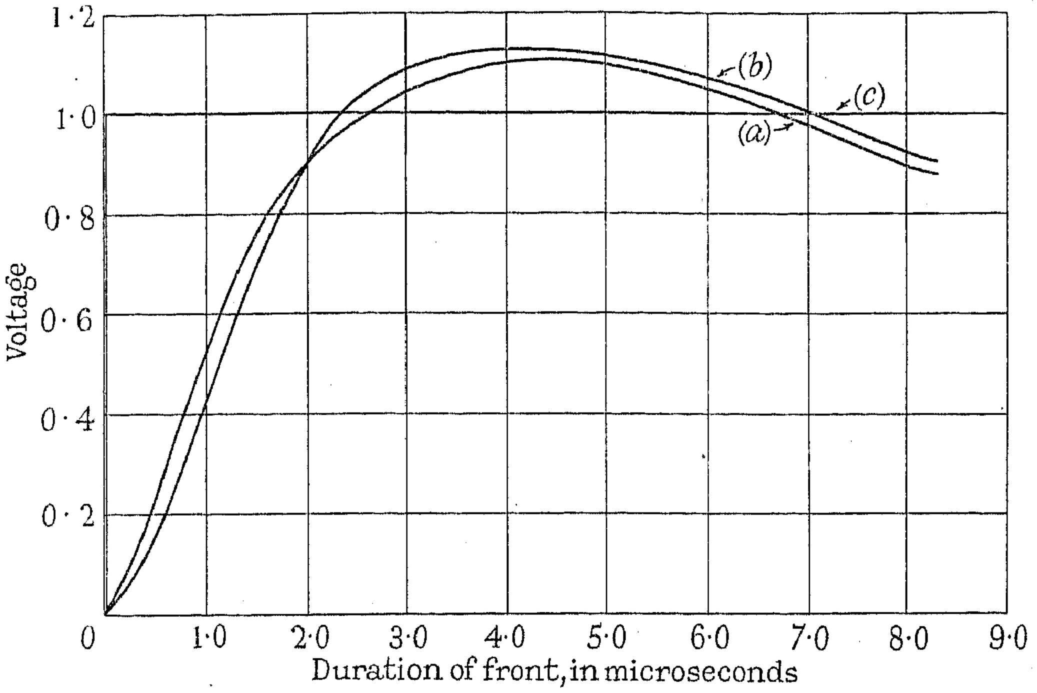

Fig. 4.—Calculated output waves of two surge absorbers having (*a*) 94 % coupling and (*b*) 85 % coupling between primary and secondary windings. Line surge impedance 350 ohms, infinite rectangular incident wave (*c*), and approximately critical damping.

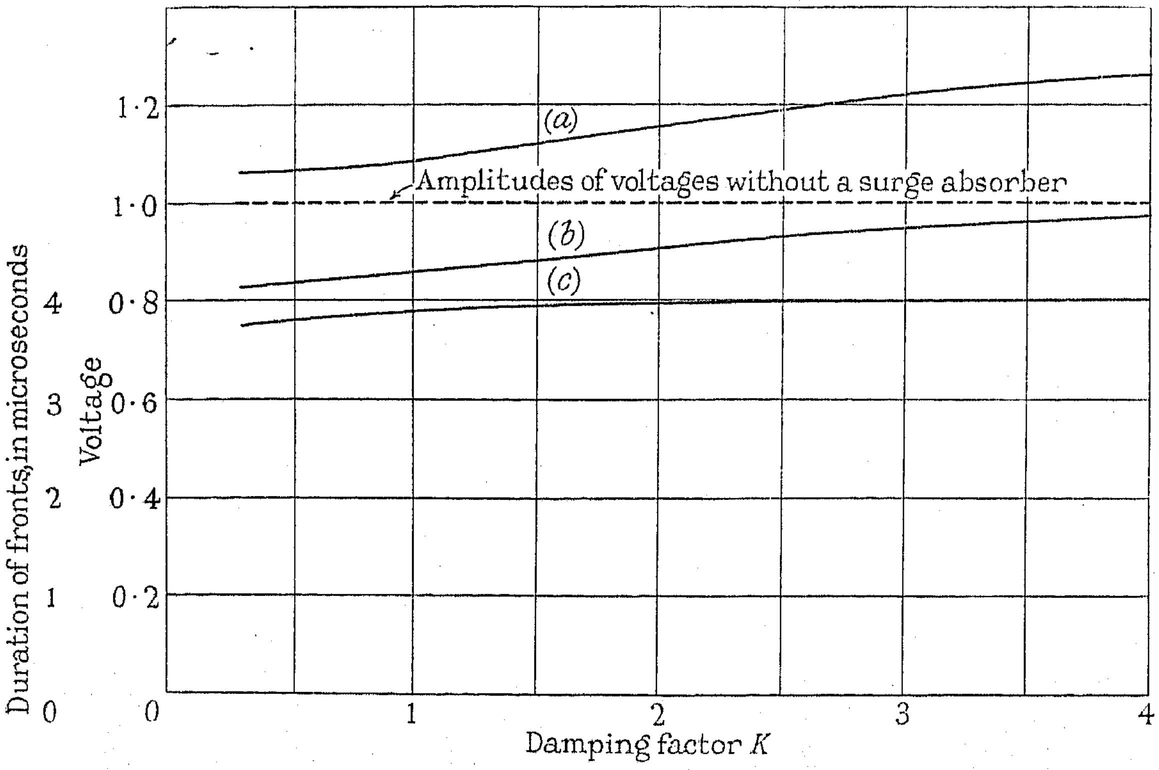

Fig. 5.—Effect of variation in secondary damping factors in surge absorbers having fixed couplings and fixed values of L_1 and C_1. Obtained experimentally.

(*a*) Amplitudes of output waves for 0·2/40 incident wave.
(*b*) Amplitudes of output waves 0·5/5 incident wave.
(*c*) Durations of fronts of output waves for 0·2/4 incident wave. Line surge impedance = 350 ohms.

Further, with finite incident waves and tight couplings as obtain in the surge absorber, the amplitude increase is effectively controlled by the secondary damping (the third controlling factor), and this is illustrated by the experimentally determined curves in Fig. 5. It is seen that with suitable damping and practical incident waves little or no amplitude increase can be maintained. Fig. 16 also illustrates the point well with the 0·5/5 wave.

(e) The Calculation of Surge-Absorber Performance.

The voltage wave from an absorber arranged as in Fig. 1(*b*) and protecting a transformer from an infinite rectangular incident wave $E1$ can be accurately calculated from:—

$$\frac{2}{SL_1C}\cdot\frac{p+\dfrac{R_2}{L_2}}{p^3+\left(\dfrac{R_2}{SL_2}+\dfrac{Z_1}{SL_1}\right)p^2+\left(\dfrac{Z_1R_2}{SL_1L_2}+\dfrac{1}{SL_1C}\right)p+\dfrac{R_2}{SL_1L_2C}}\cdot E1 \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

The explicit conditions for non-oscillation in the worst case of zero line impedance are that

$$\frac{R_2}{\sqrt{(L_2/L_1)}\cdot\sqrt{(L_2/C)}}$$

should lie in the range

$$\sqrt{\left[\frac{1+18S-27S^2}{8}\pm\sqrt{\left\{\left(\frac{1+18S-27S^2}{8}\right)^2-S\right\}}\right]} \quad (2)$$

and be greater than $\sqrt{(3S)}$, where $S = 1 - M^2/(L_1L_2)$.

Unfortunately, however, even with the infinite rectangular incident wave the above equations are cumbersome except for the case of a critically damped absorber with a coupling M^2/L_1L_2 of $\frac{2}{3}\sqrt{2}$ (see equation C of the Appendix), and it has been found that the simpler equation given below suffices to enable computations on the quantitative effects of secondaries and the other constants on input waves of any form to be obtained. It is:—

$$e_2 = 2E\left[\frac{\epsilon^{-at}}{K_1}-\frac{\epsilon^{-bt}}{K_2}+\frac{b-a}{K_5(K_3-a)(K_3-b)}\epsilon^{-K_3t}\right.$$
$$\left.-\frac{b-a}{K_5(K_4-a)(K_4-b)}\epsilon^{-K_4t}\right] \quad . \quad (3)$$

where $K_1 = CL_ea^2 - a(Z_1+R_e)C + 1;$
$K_2 = CL_eb^2 - b(Z_1+R_e)C + 1;$
$K_3 = (CR_e + CZ_1 - K_5)/(2CL_e);$
$K_4 = (CR_e + CZ_1 + K_5)/(2CL_e);$
$K_5 = \sqrt{\left[C^2(Z_1+R_e)^2 - 4L_eC\right]}.$

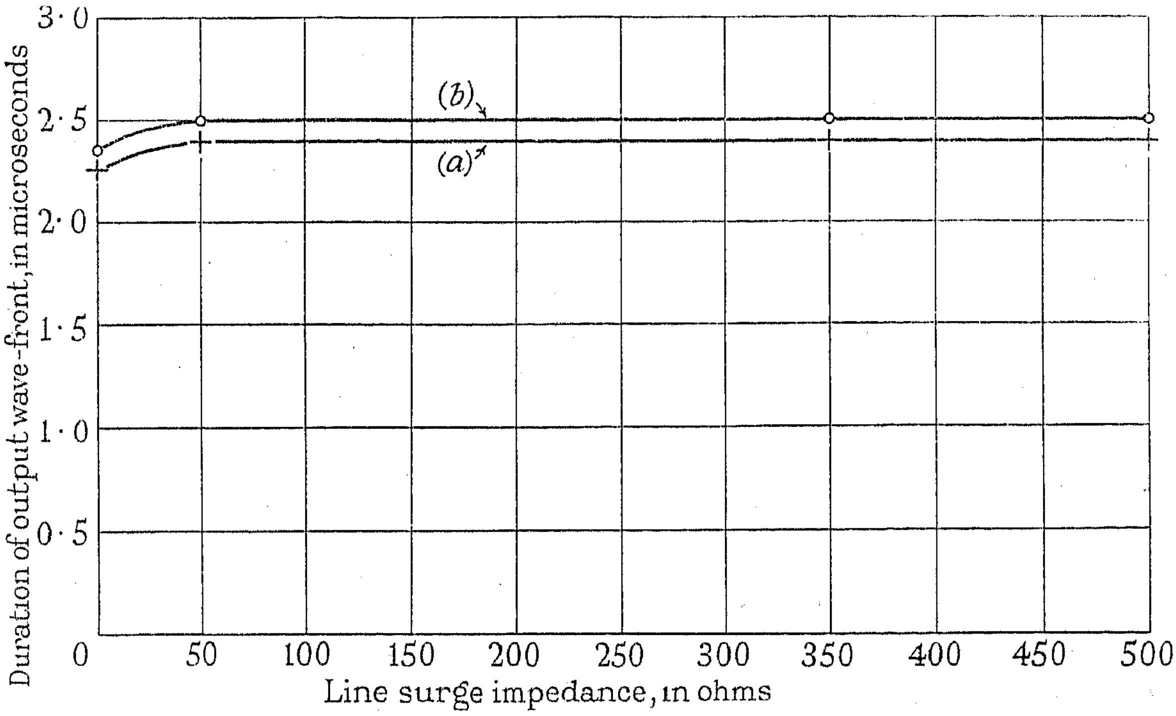

Fig. 6.—Calculated relation between line surge impedance and durations of fronts of output waves of a surge absorber for (*a*) 1/5 incident wave, and (*b*) 1·5/40 incident wave.

As will be evident, the calculated curves of the surge-absorber performance have been extended into the oscillatory zone, and to obtain these the appropriate equations were used, the simplified form of which is

$$e_2 = 2E\left[\frac{\epsilon^{-at}}{K_1}-\frac{\epsilon^{-bt}}{K_2}-\frac{2}{K_6}\sqrt{(CL_e)}\cdot\epsilon^{-\left(\frac{Z_1+R_e}{2L_e}\right)t}\right.$$
$$\left.\times\left\{\frac{\cos\left(\dfrac{K_6t}{2CL_e}-\theta_1\right)}{\sqrt{K_1}}-\frac{\cos\left(\dfrac{K_6t}{2CL_e}-\theta_2\right)}{\sqrt{K_2}}\right\}\right] \quad (4)$$

where $K_6^2 = -K_5^2$.
$\theta_1 = \text{arc tan } (CZ_1 + CR_e - 2CL_ea)/K_6.$
$\theta_2 = \text{arc tan } (CZ_1 + CR_e - 2CL_eb)/K_6.$

All the equations, of course, can be applied also to the conditions where there is a flashover on the line side of the absorber by adding the output voltage waves for suitable positive and negative input waves separated by an appropriate time-interval.

It may be of interest to discuss the effect of variation in incoming line surge impedance with the aid of these equations. The duration of fronts of the e_2 voltage using 0·5/5 and 1·5/40 incident waves were calculated for four different line impedances, and the results are shown in Fig. 6. It is seen that the flattening is practically independent of the line impedance over the range of 0 to 500 ohms, and this conforms with the results shown in Table 2 of Section 5(*c*) (ii*e*). Even if the impedance is actually zero there is only a slight reduction in flattening, and this is confirmed by the duration of the collapse of voltage as shown, for example, in Fig. 18(*c*).

(5) THE MEASUREMENT OF THE STRESSES IN TRANSFORMER WINDINGS UNDER THE VARIOUS CONDITIONS ARISING FROM LIGHTNING, AND THEIR REDUCTION BY MEANS OF WAVE-FLATTENING DEVICES

(a) General Remarks.

During the course of the past few years the authors have studied experimentally the effect of various kinds of lightning protective devices on the stresses arising in transformer windings. A large number of testing arrangements have been used and results have been obtained in transformers covering all ratings and voltages.

To present this mass of data here, however, would merely serve to embarrass the reader. It has therefore been decided to give the complete results dealing with the stresses in one transformer winding (one phase of a 37 500-kVA, 88-kV, 3-phase star-connected transformer —called transformer No. 1 in what follows) and the protection afforded by various wave-flatteners under all relevant test conditions, and to correlate these data with those found on other transformers having different values of α, ratings, and periodic times, by briefly quoting the appropriate and more important parts of the findings. In all cases the insulation in the axial direction in all the transformer windings was designed in accordance with the requirements of present-day practice, as indicated in the various purchasing specifications. The results are presented in such a form that comparison of the stresses in the various transformers with different applied transient wave-forms is possible.

The experimental results on which the curves in this paper are based are first obtained using impulses of convenient voltage and measuring the voltages between coils or between turns at different points in the winding.

The point of interest here, however, is the actual relative gradients, which, of course, are dependent on the local amounts of intercoil and interturn insulation. Therefore, the results are first plotted with voltage gradient in kV per in. in this insulation as ordinate, against position in the winding as abscissa for the test terminal voltage.

The obvious basis, of course, for the required comparison of different transformers under various terminal voltage conditions is the relationship between their relative stresses under amplitudes of impulses which are equal to or are in some arbitrarily fixed ratio to the maximum amplitudes which they can ever experience in practice. The maximum voltage of any particular impulse that can occur on a transformer is mainly dependent on the ratio of the line or bushing impulse sparkover to the line operating voltage to earth. This ratio varies with the impulse wave-shape and with the voltage rating. (It also varies to some extent from system to system even for the same voltage, but this factor has been neglected.)

Provided, then, that the correct amplitude relations for the different applied terminal impulse waves* and the generally accepted ratios of the line sparkover to the line operating voltage are observed, and that the voltage-gradient curves are scaled up from the test voltages allowing for these factors (this is admissible since the nature and percentage distribution of the internal voltages are practically independent of the magnitudes of the impulse voltages), then curves are obtained which enable the required comparisons to be made. Actually, an arbitrary voltage-gradient scale has been chosen such that 100 units correspond to the maximum gradient in No. 1 transformer for the 0·2/40 impulse, and all the other gradient distribution curves are based on this. It will be realized, of course, that the relative impulse strengths for the different transformers and for the different impulses are inversely proportional to the maxima of the several curves, and, since these maxima are the weakest points in the windings, failure would first be expected to occur there.

(b) Description of the 37 500-kVA, 88-kV, 3-phase, star-connected, 50-cycle transformer employed in the Full Range of Tests.

As stated, one phase of this transformer—called No. 1 —was used. The windings were of the disc type and had 86 sections which were insulated in accordance with the requirements of the purchaser's specification. The end-turn insulation was heavily reinforced and graded and there was also some reinforcement in the tapping range and at the earthed neutral. Since the greater number of oscillograph measurements were made between coils and between turns, so necessitating a large number of connecting points, the transformer was used in air but was surrounded by a dummy tank. Like all the others it was tested unenergized.

The value of α for this transformer was 20, and the frequency of its fundamental oscillation was 26 000 cycles per second, giving a periodic time T in air of 39 microseconds.

The changes in the terminal voltages of and the gradients in this transformer were fully examined under different surge conditions when it was protected by condensers having various capacitances, by an inductance coil, and by a surge absorber. The results are dealt with in Sections (*c*), (*d*), and (*e*), which follow.

(c) Travelling-Wave Conditions.

(i) Test-circuit considerations.

Pure travelling-wave conditions are the most readily simulated. Since in practice a wave on a transmission line moving towards a terminus is not affected by the circuit conditions at the terminus until the wave reaches it, so the output wave of the impulse-generator circuit should be unaffected by the load; that is, the insertion of apparatus between the generator and the transformer should not affect the output wave. Such a circuit is shown in Fig. 7, C_e representing the transformer effective earth capacitance.

The circuit, of course, can be adjusted to give any wave

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* Impulse-ratio figures vary with sparkover distance and wave-shape. In addition, final agreement even for any specified condition has not yet been obtained between authorities. It would therefore be cumbersome and difficult to take full cognisance of these factors in a paper such as this which deals generally with apparatus covering a wide range of voltage, and thus round figures have been used [see Bibliography, (31), (32), (33)]. For the 0·2/40 and 1·5/40 travelling waves an impulse ratio of 1·3 has been assumed, and the same figure has been used for the 5/40 wave when flashing-over on the front. For the 0·5/5 wave the figure taken is 1·7. All these figures apply to the case where the transformer was surged separately or where it was protected by a surge absorber, since in the latter case the voltage at the line side—where flashover occurs—is of the same order of steepness as that of the incident voltage. When condenser protection is employed, however, the rate of rise of voltage at the flashover point is lower and hence the round figure of 1·3 has again been taken.

The impulse ratios with the direct strokes are considered separately in Section 5(*e*).

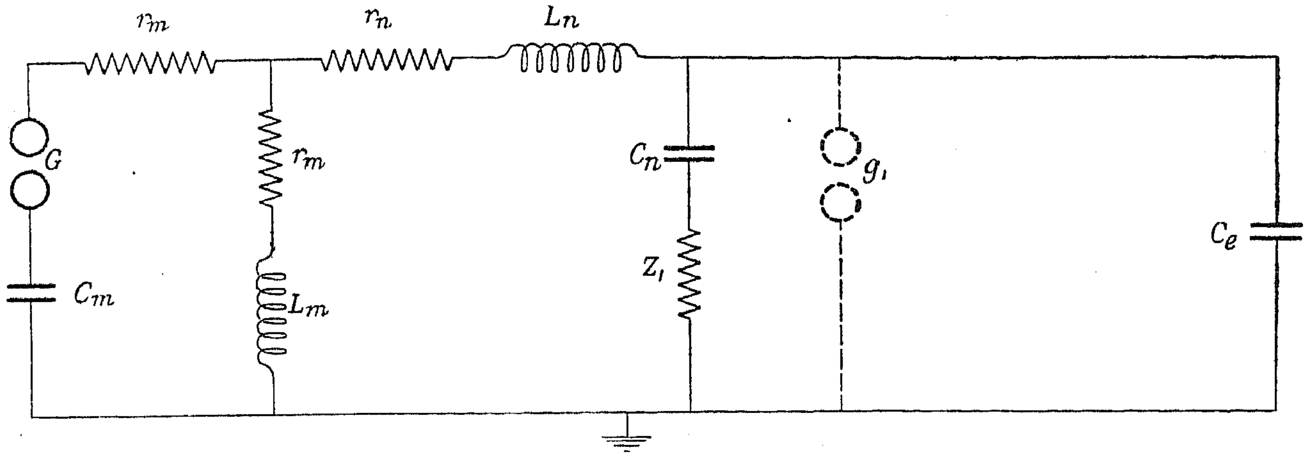

Fig. 7.—Surge generator for the simulation of transmission-line travelling waves. For an output wave of $E(\epsilon^{-at} - \epsilon^{-bt})$ and a line surge impedance Z_1, there are: $r_m + r_n = Z_1$; $L_m = C_m r_m^2$; $a = r_m/L_m$; $Z_1^2 = L_n/C_n$; $b = Z_1/L_n$. C_e = capacitance of transformer under test.

of the form $E(\epsilon^{-at} - \epsilon^{-bt})$, and throughout this Section 0·5/5, 1·5/40, and 0·2/40 waves* have been used as being representative of the more dangerous travelling waves found.

The 0·5/5 wave is one commonly used and is considered typical of surges formed by a direct stroke (followed by a flashover) sufficiently far from the transformer to allow of the line surge impedance being included in the circuit, yet not sufficiently far away for the wave to be excessively distorted or flattened. The 1·5/40 wave is the wave which comes within the range of long waves specified in the tentative specifications, and represents one which has perhaps travelled many span lengths before reaching the transformer. The 0·2/40 wave was used as it combines the effects of a very fast front and a long back and probably represents the most dangerous travelling wave which could be formed.

The values of the equivalent surge impedances of the generators used were 350 ohms, and the laboratory transmission line was designed to match this value.

(ii) 0·2/40 wave.

(ii*a*) *Gradients Unprotected and Protected by Surge Absorbers and by Condensers.*

The oscillograms in Fig. 8 give the voltages at the transformer terminal when it is protected by three of the protective devices, while Fig. 9 shows the relative gradient-distribution curves arising from these four terminal voltages. It will be seen that the surge absorber gives a 2·86-fold increase in strength of the winding against 1·21-fold and 2·5-fold increases for the small and large condensers respectively. Figs. 8(*e*) and 8(*f*) are a typical pair of oscillograms showing the reduction in intercoil voltage obtained by employing the surge absorber.

The effect of the reinforcement in this particular transformer is well shown. The maximum voltages naturally occurred at the line end of the winding—the strength here is increased about 10-fold by using the absorber—but the maximum gradients occur where the insulation is normal, i.e. at points in the winding 15 to 30 % from the line end. It is here that the unprotected winding would break down and, in fact, a similar winding when impulse-tested to destruction in the laboratory failed in this region.

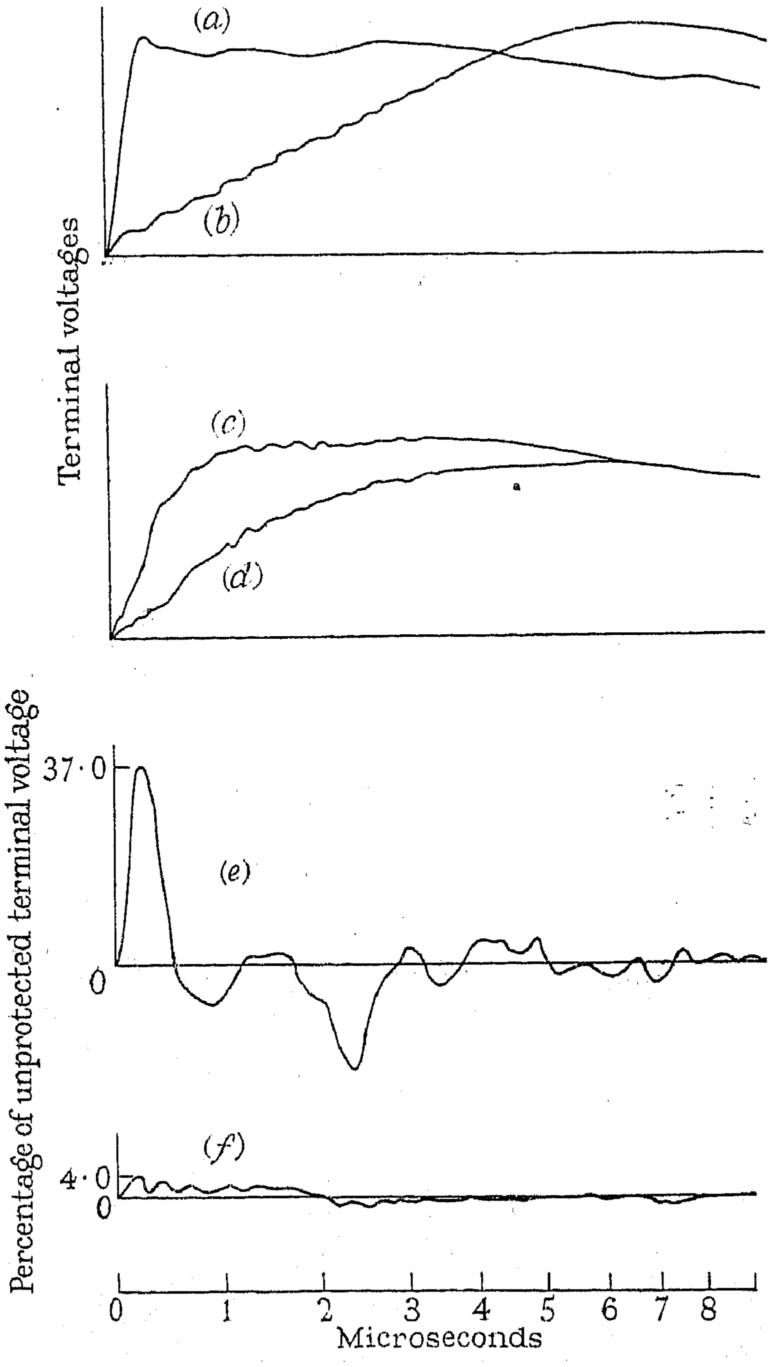

Fig. 8.—Voltages under 0·2/40 travelling-wave conditions at the terminal and in the winding of transformer No. 1. Z_1 = 350 ohms.

(*a*) Terminal voltage when unprotected.
(*b*) Terminal voltage when protected by the surge absorber.
(*c*) Terminal voltage when protected by the 1 170-μμF condenser.
(*d*) Terminal voltage when protected by the 6 000-μμF condenser.
(*e*) Intercoil voltage when unprotected; corresponding to terminal voltage (*a*).
(*f*) Intercoil voltage when protected by the surge absorber; corresponding to terminal voltage (*b*).
(*b*), (*c*), and (*d*) are to the same voltage scale as (*a*). (*e*) and (*f*) are to the same voltage scale.

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* In this paper the fronts have been described as 1·25 × (the time-interval between points on the wave-front where the voltage is 10 % and 90 % respectively of the impulse crest value).

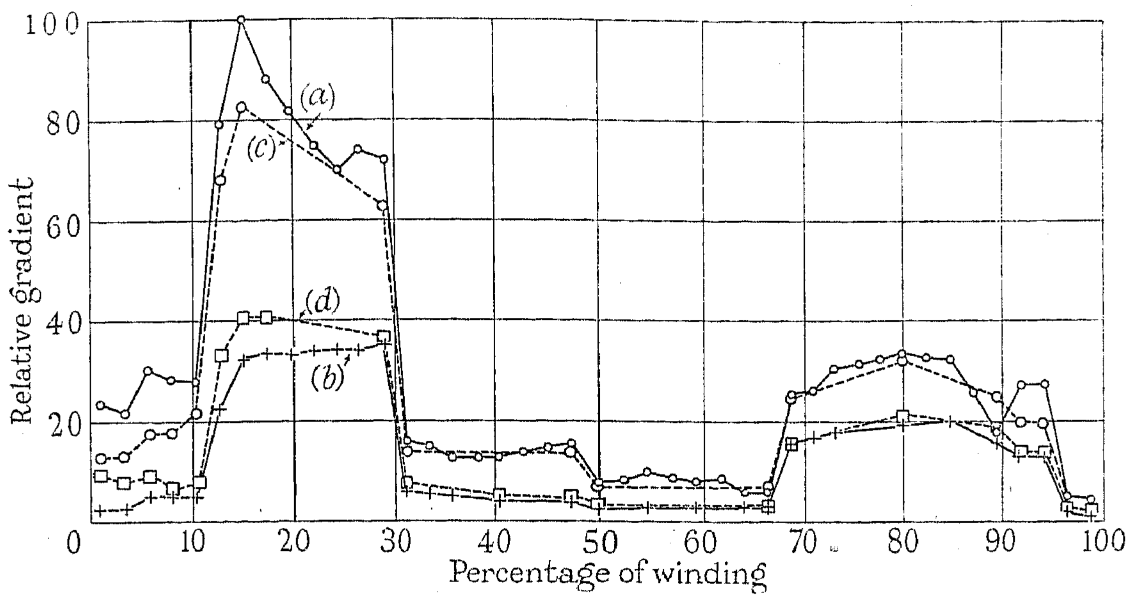

Fig. 9.—Relative intercoil gradients under 0·2/40 travelling-wave conditions in No. 1 transformer winding, when (*a*) unprotected, (*b*) protected by the surge absorber, (*c*) protected by the 1 170-μμF condenser, and (*d*) protected by the 6 000-μμF condenser. Assumed impulse ratio = 1·3.

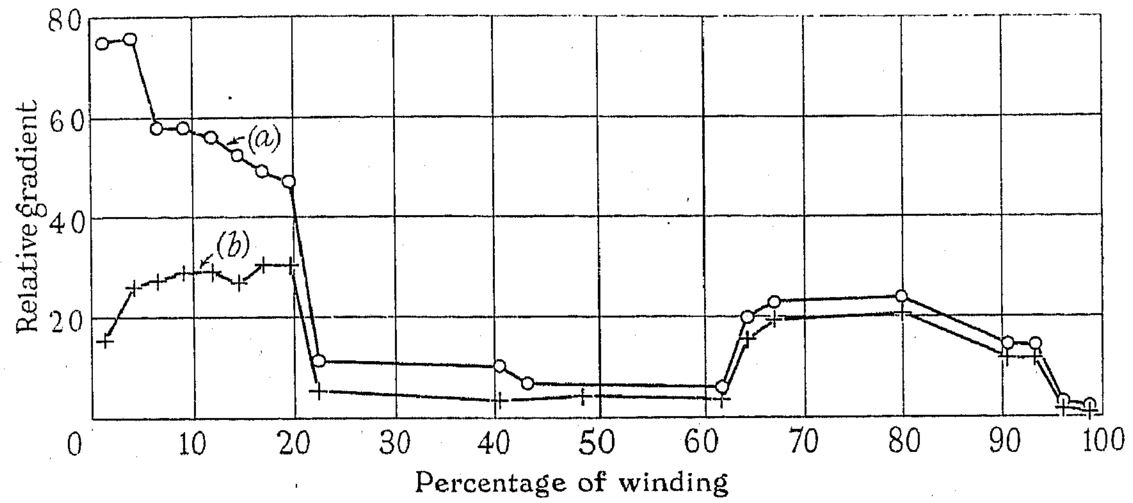

Fig. 10.—Relative gradients under 0·2/40 travelling-wave conditions in No. 2 transformer, i.e. No. 1 transformer with the reinforced end-sections removed, when (*a*) unprotected and (*b*) protected by the surge absorber. Assumed impulse ratio = 1·3.

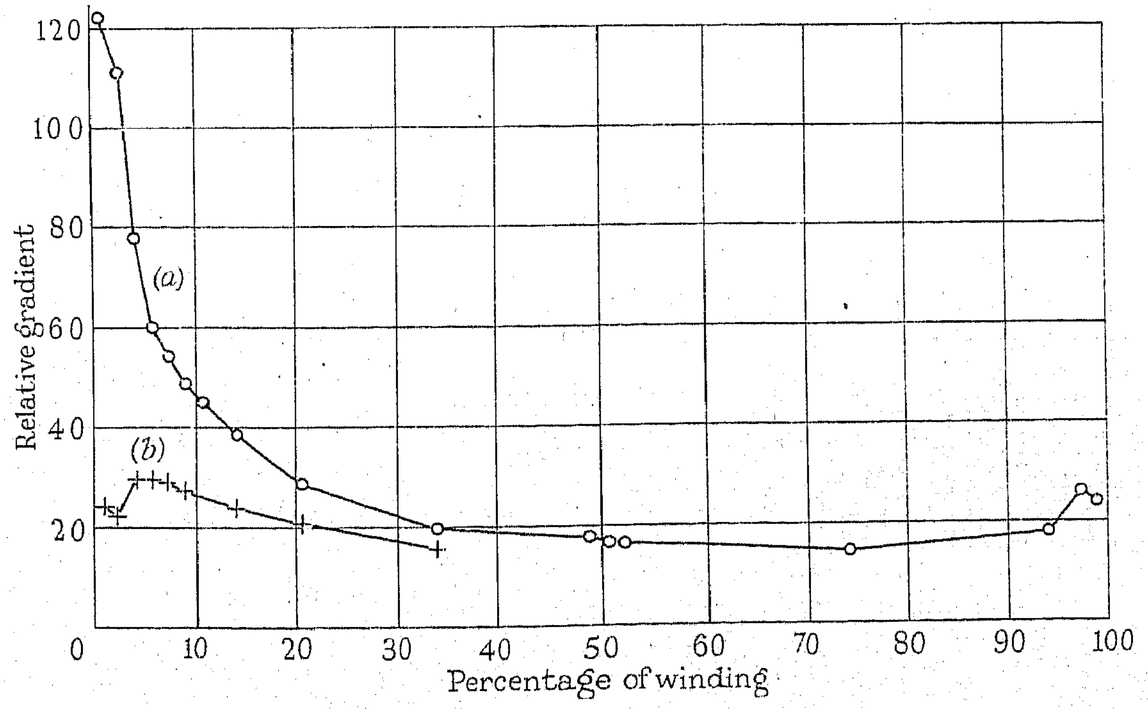

Fig. 11.—Relative gradients under 0·2/40 travelling-wave conditions in No. 3 transformer when (*a*) unprotected and (*b*) protected by the surge absorber. Assumed impulse ratio = 1·3.

There is a smaller maximum gradient near the reinforced neutral which is, however, unimportant compared with the gradients nearer the line end. This is a characteristic found under all the conditions of test employed.

(ii*b*) *Reinforcement.*

The effect of reinforcement* in windings is often debated, and uniformly insulated windings have been built for the purpose of experimentally determining their behaviour under transient conditions. A complete discussion on this subject would, however, be out of place in this paper, but, in order to illustrate that the efficacy of the wave-flattening method of protection is independent of reinforcement, distribution curves have been drawn for two cases.

The first refers to the winding under discussion, so that comparison is simple. In this case the experiment was carried out simply by removing the reinforced end-turns—the transformer now being called No. 2—and the distribution curves are shown in Fig. 10.

The second relates to a specially built transformer. This transformer—called No. 3—was used in air, had an earthed neutral, a rating of 1 800 kVA, an operating voltage of 33 kV, an α of $16 \cdot 7$, and a periodic time of 57 microsec. The distribution curves are shown in Fig. 11.

With regard to Nos. 1 and 2 transformers, it will be noted that the removal of the reinforcement has increased the unprotected $0 \cdot 2/40$-wave strength in the ratio of $1 \cdot 33$ to 1, and that the gradients near the neutral are slightly affected. With regard to Nos. 2 and 3 transformers, it will be seen that the maximum gradients now occur at the line ends of the windings.

(ii*c*) *Comments on the Degree of Flattening.*

It has been stated† that to obtain a uniform distribution a wave-front flattening of about $0 \cdot 4T$ is necessary, and this is in general quite true. In the present case, for instance, Fig. 12 is clearly roughly in agreement (here $0 \cdot 4T = 0 \cdot 4 \times 39 = 16$ microsec. approx.). The statement has, however, been employed as an argument to show the practical impossibility of protecting by flatteners. The flaw in this argument is, of course, that with transformers of modern design it is quite unnecessary to proceed to the limit of uniform distribution, which, in the present case of Fig. 12, would involve an increase in the strength of some $11 \cdot 8$-fold. Clearly this is unnecessary and, as has already been stated, what is necessary for satisfactory operation is an increase of about 3-fold. From Fig. 12, obtained by using linear fronts, this is seen to require about $4 \cdot 6$ microseconds, but of course this curve does not take account of the shift down the winding of the point of maximum gradient as the applied wave-front becomes less steep.

All the authors' experience on transformers of varying periodic times and α's shows that 5 microseconds' flattening is adequate for giving the required reductions. Actually in many cases a smaller flattening is sufficient, as evidenced in the case of No. 6 transformer, where the surge absorber used flattened only to $3 \cdot 5$ microseconds.

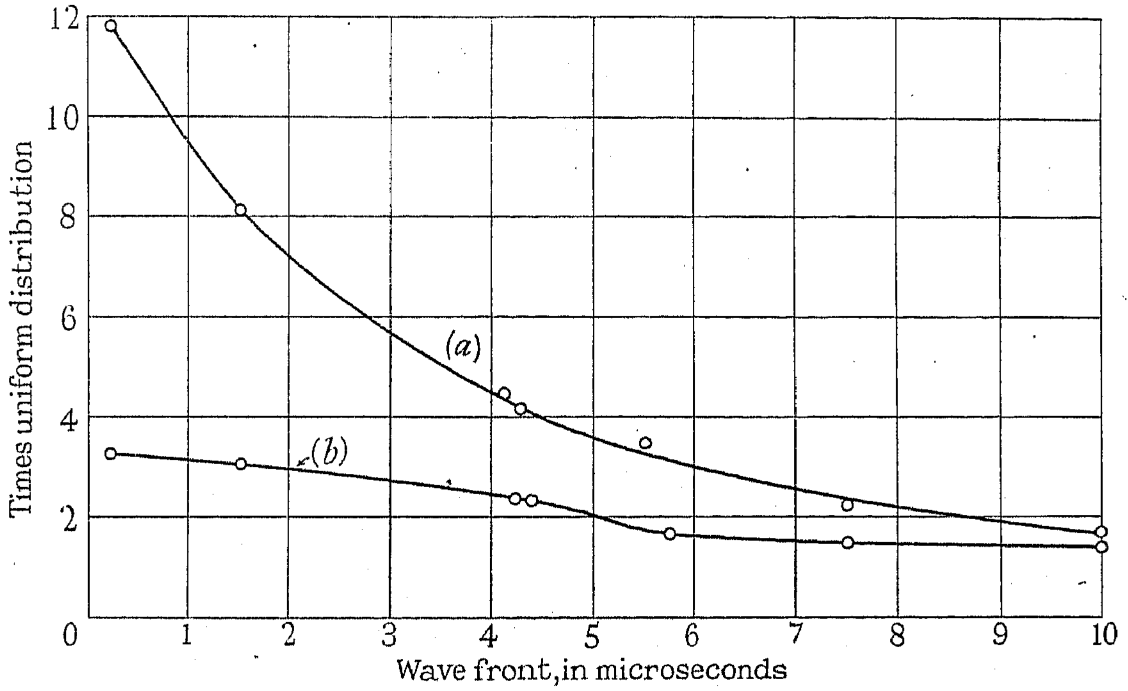

Fig. 12.—Experimental relation between terminal-voltage wave-front steepness and voltage gradient between adjacent coils at (*a*) $12 \cdot 8$ % and (*b*) $68 \cdot 6$ % from the line end.

(ii*d*) *Between-turn Voltages.*

Fig. 13 gives the gradients between the first two turns of each section for the upper part of the winding.* The ordinate scale, of course, is the same as those for the other curves, the reason for the lower values of the relative gradients here lying in the construction of this type of winding in sections. It will be seen, however, that the surge absorber here gives the same order of reduction in the stresses. The conductor in this case, in accordance with the requirements of the purchaser, was heavily insulated, but this has been found by experiment to apply also to cases where only thin conductor coverings are employed.

It was also found that there was a corresponding reduction in the stresses between turns inside the coils when the applied wave-front was altered from $0 \cdot 2$ to $5 \cdot 2$ microseconds. This is illustrated in Table 1, which

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* See Bibliography, (23), (34).

† *Ibid.*, (35).

* See Bibliography, (36).

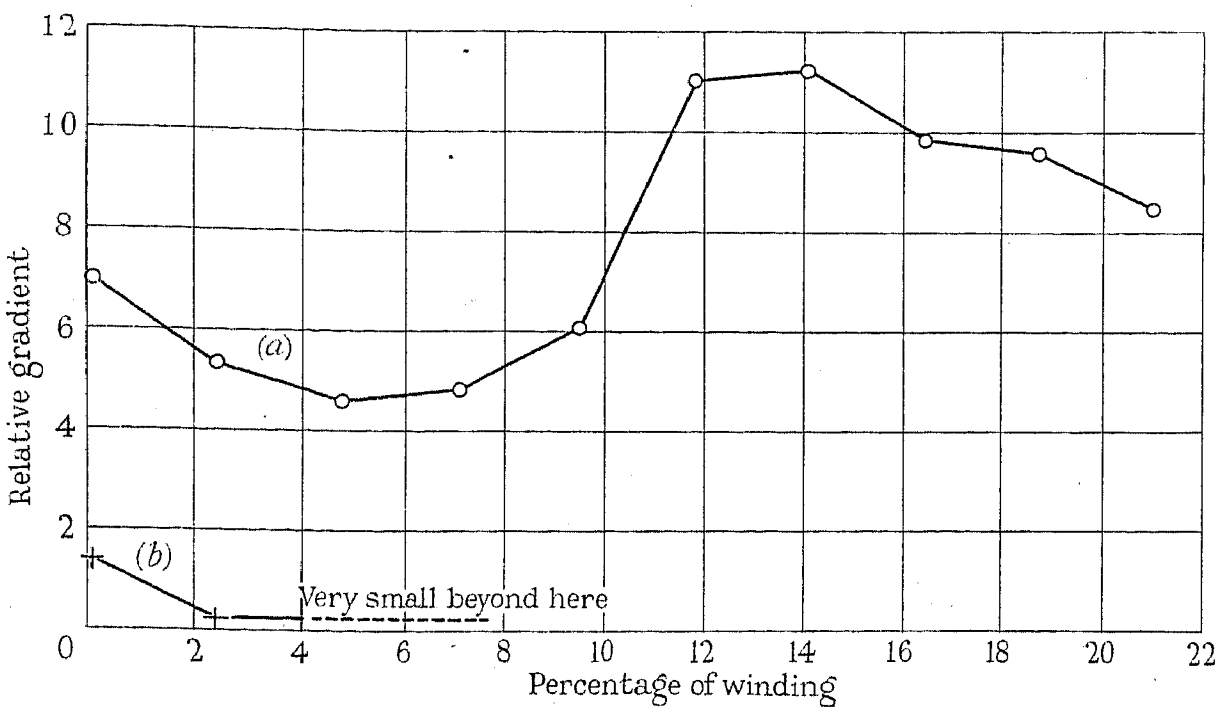

Fig. 13.—Relative interturn gradients in the first 21 % of the winding of No. 1 transformer (based on the voltages between the first 2 turns of each section) under 0·2/40 travelling-wave conditions, when (*a*) unprotected, (*b*) protected by the surge absorber. Assumed impulse ratio = 1·3.

gives the ratios of the stresses caused by the 5·2-microsecond front to the stresses caused by a 0·2-microsecond front for the worst points in two pairs of sections in different parts of the winding.

Table 1

Position	Ratio: $\frac{\text{Max. stress with } 5\cdot2\text{-}\mu\text{sec. front}}{\text{Max. stress with } 0\cdot2\text{-}\mu\text{sec. front}}$
A	0·2
B	0·28
C	0·19
D	0·23

Position A.—Between a pair of opposite turns in the first two sections at the line end.

Position B.—Between a pair of opposite turns in the first two unreinforced sections.

Position C.—Between two adjacent turns in the first section.

Position D.—Between two adjacent turns in the first unreinforced section.

As would be expected, the reduction in the gradients between turns by flattening the wave-front to 5·2 microseconds is rather greater than that between coils.

(ii*e*) *Line Surge Impedance.*

So far all the results have referred to the case where the connected line surge impedance was 350 ohms. The performance of the surge absorber is, however, practically independent of normal alterations in line surge impedance. This is illustrated in Table 2. The gradients shown were measured in the unreinforced part of the winding.

Table 2

Line surge impedance	250 ohms	350 ohms	500 ohms	600 ohms
Relative gradient .	36·2	35·7	35·4	34·2

(iii) 1·5/40 travelling wave.

The distribution curves for this case are shown in Fig. 14. The maximum gradient in the unprotected transformer is now only 71 % of that obtained with the 0·2/40 wave. The distribution curves for the case of the protected transformer are, however, very nearly the same for both waves. Thus, although the surge absorber is now not giving such large decreases in gradients as before, the level of the gradients in the protected case is practically unaltered. Thus the nature and magnitude of the voltage on the protected side of the absorber is reasonably independent of the incident wave-front.

The distributions for the 1 170-$\mu\mu$F and 6 000-$\mu\mu$F condensers are very similar to those shown in Fig. 9. The terminal waves are shown in Fig. 15 for the case of the surge absorber.

(iv) 0·5/5 wave.

The terminal waves for this case are shown in Fig. 16 and it will be noted that the original wave is now short enough to permit 15 % reduction in the amplitude of the transformer terminal voltage when the surge absorber is put in circuit.

The voltage-gradient distribution curve is shown in Fig. 17, and it is noteworthy that in this particular case the maximum gradient without the surge absorber is some 14 % greater than that obtained with the 0·2/40 wave. Again, however, the distribution in the protected case is very similar to that found with the 0·2/40 wave, so that the statement made previously that the level of protection of the surge absorber is reasonably independent of wave-front steepness may be enlarged to include the fact that under travelling-wave conditions it is also reasonably independent of wave-shape generally.

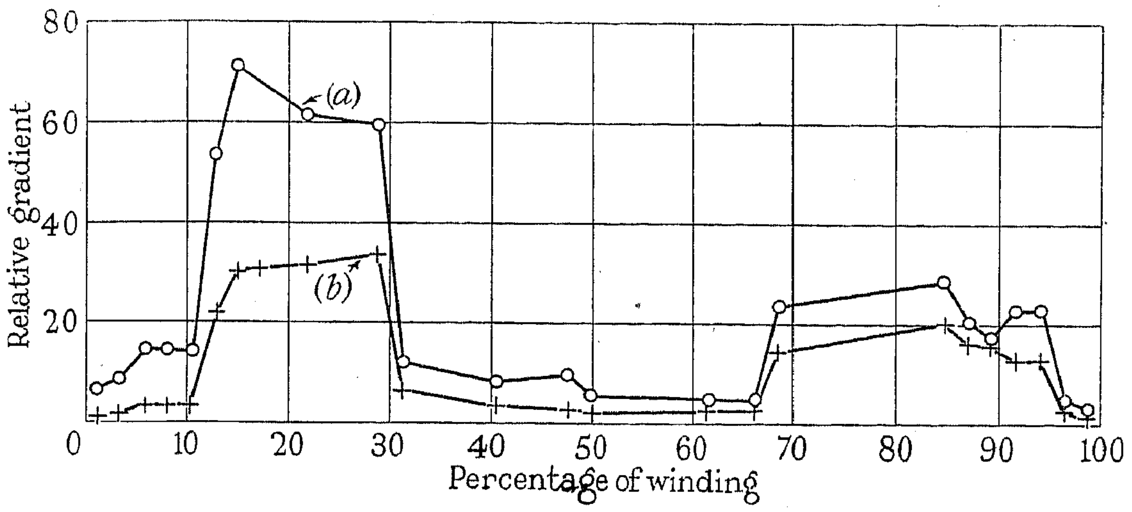

Fig. 14.—Relative intercoil gradients under 1·5/40 travelling-wave conditions in the No. 1 transformer winding when (*a*) unprotected, (*b*) protected by the surge absorber. Assumed impulse ratio = 1·3.

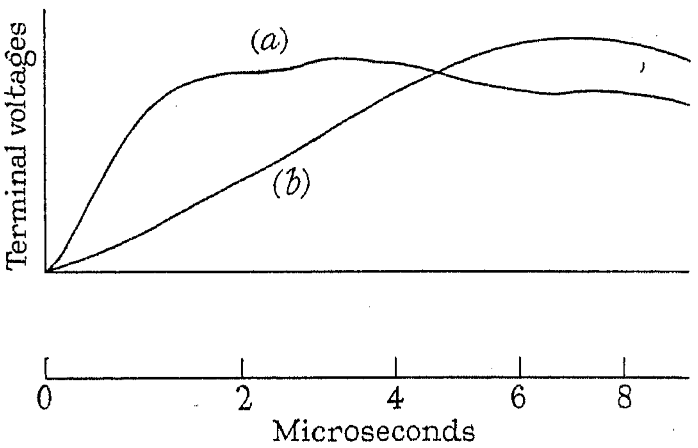

Fig. 15.—Voltages at the terminal of No. 1 transformer under 1·5/40 travelling-wave conditions, (*a*) when unprotected, (*b*) when protected by the surge absorber. Z_1 = 350 ohms.

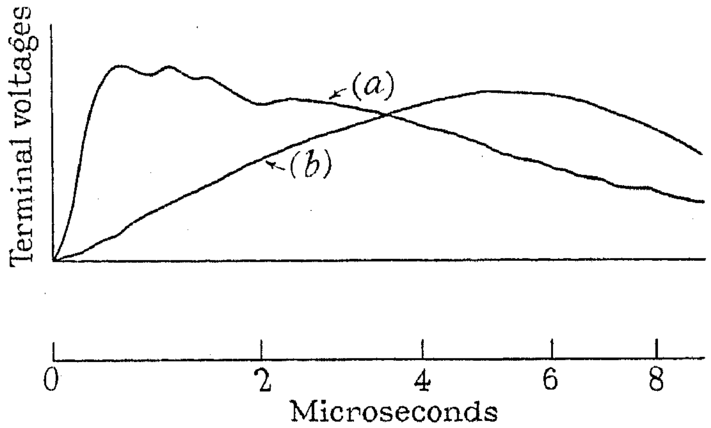

Fig. 16.—Voltages at the terminal of No. 1 transformer under 0·5/5 travelling-wave conditions, (*a*) when unprotected, (*b*) when protected by the surge absorber. Z_1 = 350 ohms.

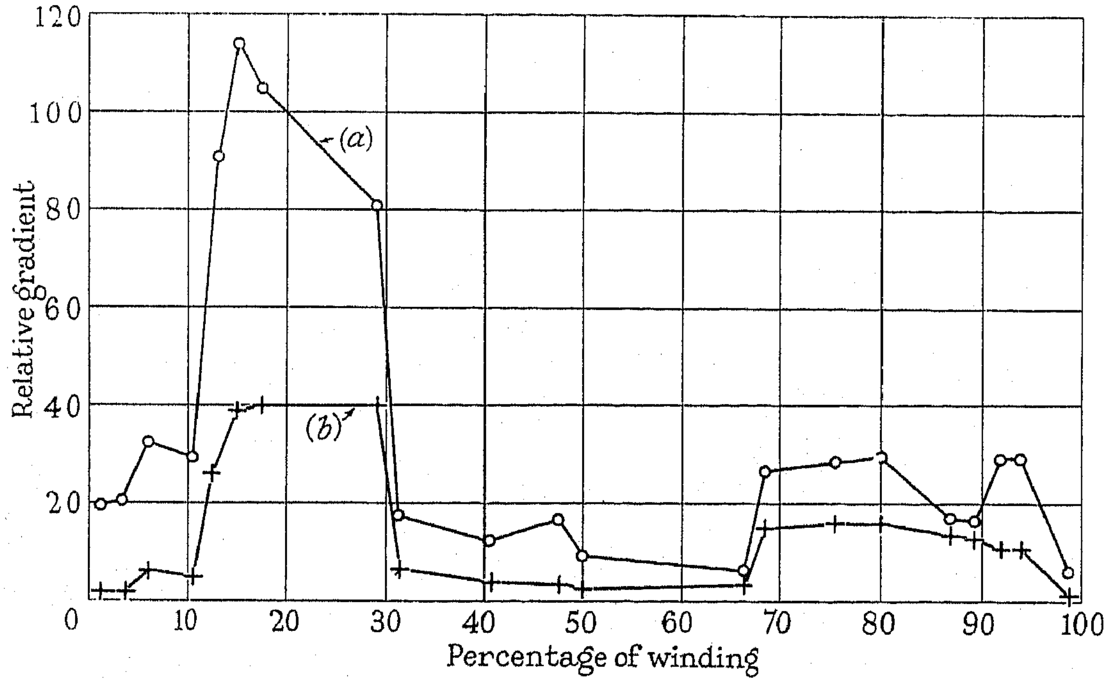

Fig. 17.—Relative intercoil gradients under 0·5/5 travelling-wave conditions in the No. 1 transformer winding, (*a*) when unprotected, (*b*) when protected by the surge absorber. Assumed impulse ratio = 1·7.

(d) Travelling-Wave Flashovers.

(i) Test-circuit considerations.

The flashover of a travelling wave across the transformer terminal or an adjacent insulator, or across a co-ordinating gap, due to normal voltage-increase effect is simulated by employing the travelling-wave circuit shown in Fig. 7, and allowing flashover to occur across the spark gap g_1 which is shown dotted. In practice, flashover on the wave-front is naturally more usual than flashover on the crest, and thus in these tests g_1 is set in relation to the main gap G so that it sparks-over after about 4 microseconds on a slow wave-front which would rise to its maximum, had not sparkover occurred, in approximately 5 microseconds. Travelling-wave flashovers on fast fronts, although very likely to occur often, are not used in the tests in Sub-section (ii), simply because they do not generally impose axial stresses on a transformer winding quite as severe as do the slow-front flashovers.*

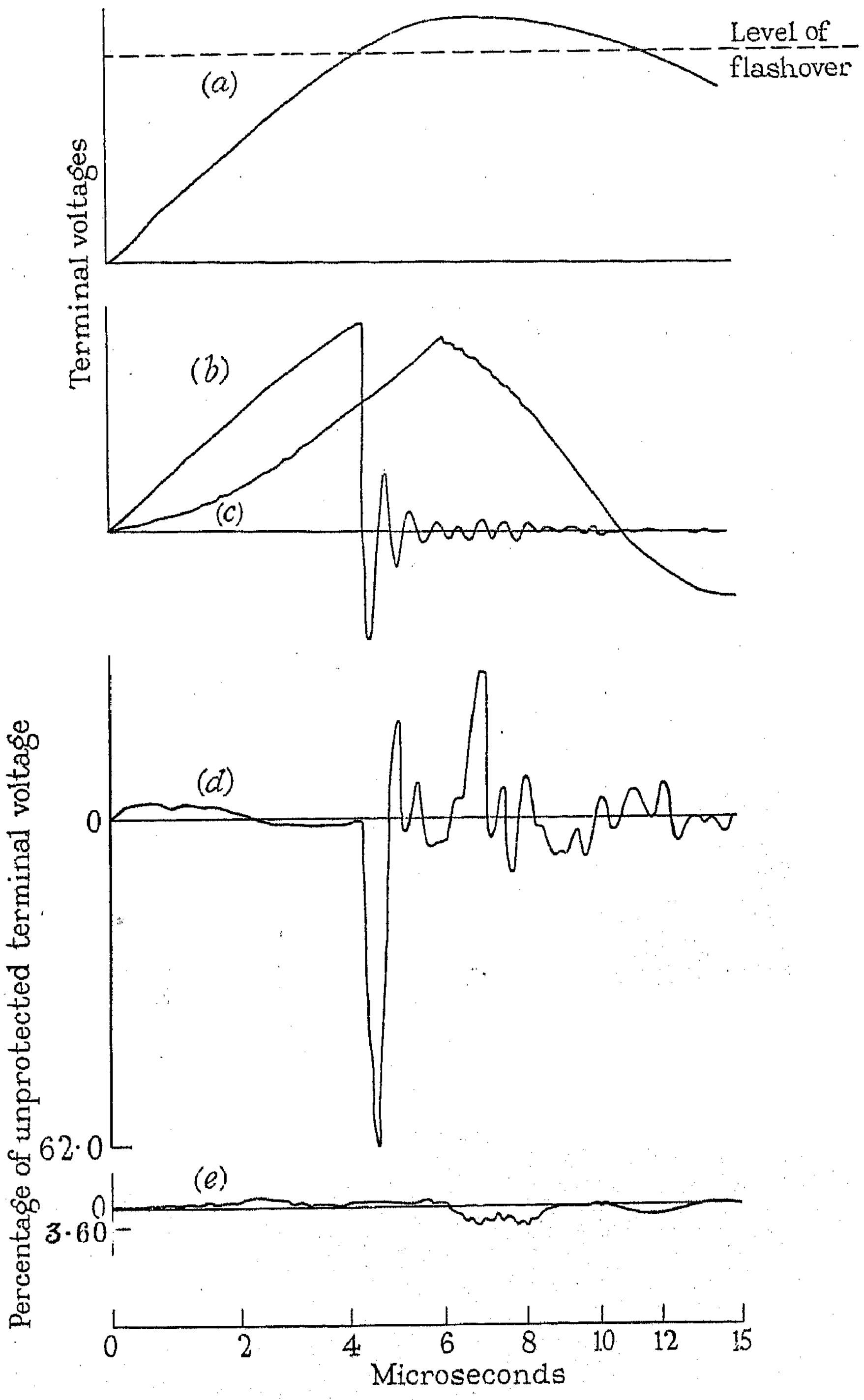

Fig. 18.—Voltages at the terminal and in the winding of No. 1 transformer, due to flashover on the front of a 5/40 travelling wave. $Z_1 = 350$ ohms.

(*a*) Terminal voltage when there is no flashover, unprotected.
(*b*) Terminal voltage when there is flashover on the front of the wave, unprotected.
(*c*) Terminal voltage when there is flashover on the front of the wave, protected by the surge absorber.
(*d*) Intercoil voltage when unprotected, corresponding to the terminal voltage (*b*).
(*e*) Intercoil voltage when protected by the surge absorber, corresponding to terminal voltage (*c*).
(*a*) and (*c*) are to same voltage scale as (*b*). (*e*) is to same voltage scale as (*d*).

In practice, of course, flashover is controlled by the magnitude of the sum of the incident and reflected voltage waves at the transformer, and the circuit in Fig. 7 truly simulates this voltage, irrespective of whether or no an absorber or other apparatus is included. Thus, if during the course of an experiment the setting of g_1 is unaltered, the change which would occur in practice when a protective device is inserted in a line without any alteration in insulation levels is truly obtained. The levels, of course, both here and in practice must be so arranged that flashover occurs at the line end of an absorber, and not at its transformer end.

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* See Bibliography, (36).

It is found in the laboratory that on flashover the voltage across the unprotected transformer tends to oscillate and give a voltage reversal, and, by increasing the total rapid collapse voltage, this reversal contributes to the axial voltages in the transformer winding. No doubt this will occur in practice and therefore no steps were taken to prevent it in the laboratory.

(ii) Flashovers near the transformer.

(ii*a*) *Gradients With and Without Surge Absorbers.*

The wave which would have been applied to the transformer if no flashover had occurred is shown in Fig. 18(*a*), while (*b*) and (*c*) show respectively the unprotected and the surge-absorber-protected transformer terminal voltages when flashover occurs. It will be seen that the very steep back and the voltage-sweep across the zero axis at the instant of flashover are eliminated by the absorber and that there is no serious oscillation.

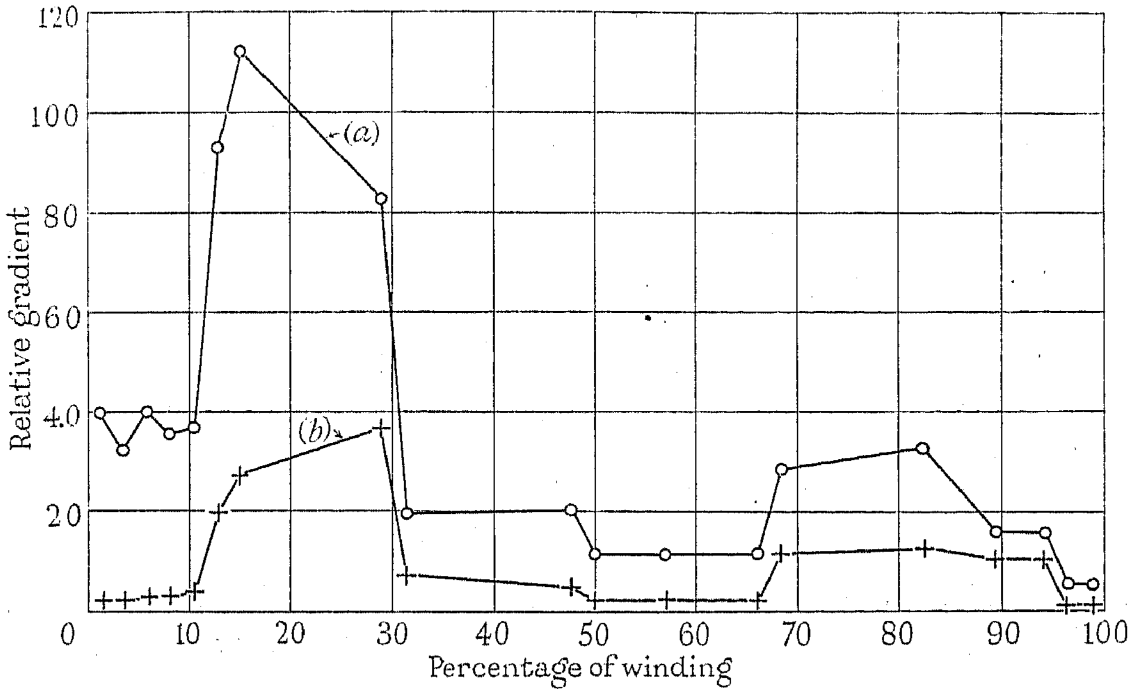

Fig. 19.—Relative intercoil gradients in No. 1 transformer winding, due to flashover on the front of a 5/40 travelling wave, (*a*) when unprotected, and (*b*) when protected by the surge absorber. Assumed impulse ratio = 1·3.

The effect on the axial voltages is well shown in Figs. 18 (*d*) and (*e*) which give the voltages between two sections. The steep back gives rise to an excessive voltage of opposite polarity to that of the applied wave, but this is eliminated in the protected case.

The voltage-gradient distribution curves corresponding to the two terminal voltages shown in Figs. 18 (*b*) and (*c*) are drawn in Fig. 19. In this case the maximum intercoil voltages have been used irrespective of polarity. It will be seen that in the case of the unprotected transformer the maximum gradient is now as great as that due to the short 0·5/5 wave, and that the absorber again reduces the stresses to approximately the same level as before.

(ii*b*) *Condensers.*

The condenser, under these flashover conditions, is not a satisfactory means of protection. The reason for this is that the local oscillatory circuit which previously consisted chiefly of the transformer capacitance, any earth resistance, and the surge-absorber inductance, capacitance, and damping, now consists only of the transformer and condenser capacitances, the earth resistance, and the inductance of a short length of conductor. Thus the time-rate of voltage collapse is of the same order of magnitude as that obtaining without the protective condenser present, and is certainly thus very much greater than that occurring with the surge absorber in circuit. In addition, the frequency of the oscillation is such that there is always the possibility of resonance with a winding harmonic. Thus unless the condensers have a capacitance great enough to give considerable reduction in the amplitude of the terminal voltage,* thus preventing flashover, they afford no protection.

The terminal voltages for the two condensers of 1 170 $\mu\mu$F and 6 000 $\mu\mu$F capacitance are shown respectively in Figs. 20(*a*) and 21(*a*), while Figs. 20(*b*) and 21(*b*) give the corresponding voltages between a pair of coils. The distribution curves are shown for the two condensers in Fig. 22, and these show that not only is there no diminution in stress [compare with (*a*) in Fig. 19], but that in one case there are actual increases. A capacitance of 0·012 μF was also employed, and this large value only reduced the level to 95 at the worst point.

(ii*c*) *Inductance Coils.*

With regard to a plain inductance coil, provided it is of adequate size, it is found, as would be expected, that if a flashover occurs at its line end there is no rapid collapse of voltage because the frequency of the oscillation round the local circuit is comparatively low. The oscillation is only damped by the inherent constants of the circuit, of course, but in general it does not necessarily give rise to any severe transformer gradients.

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* With insulation levels at the substation equal to those on the line, the capacitance would require to be of such a value that it reduced the amplitude of an incoming wave by the order of half. For various wave-shapes this can be calculated from the equation in 4(*a*).

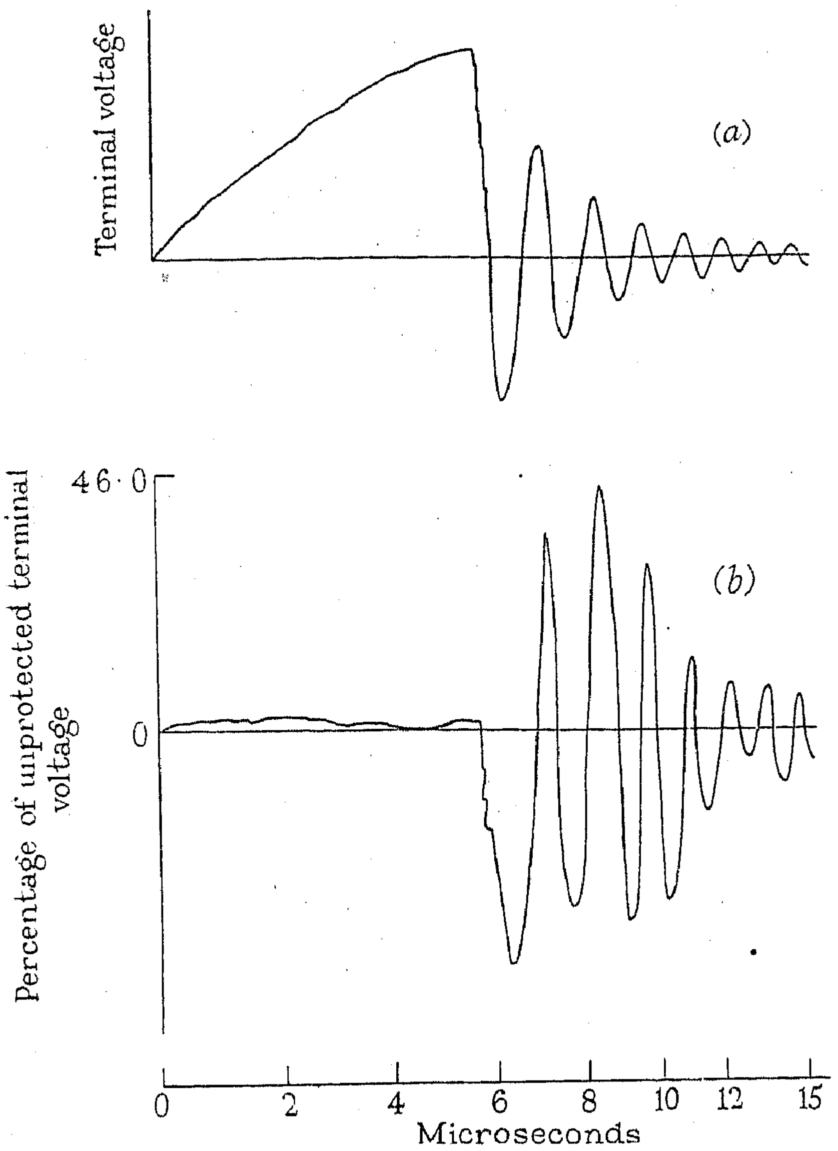

Fig. 20.—Voltages at the terminal and in the winding of No. 1 transformer, due to flashover on the front of a 5/40 travelling wave, when protected by a 1 170-$\mu\mu$F condenser. $Z_1 = 350$ ohms.

(*a*) Terminal voltage to same scale as Fig. 18(*b*).
(*b*) Intercoil voltage to same scale as Fig. 18(*d*).

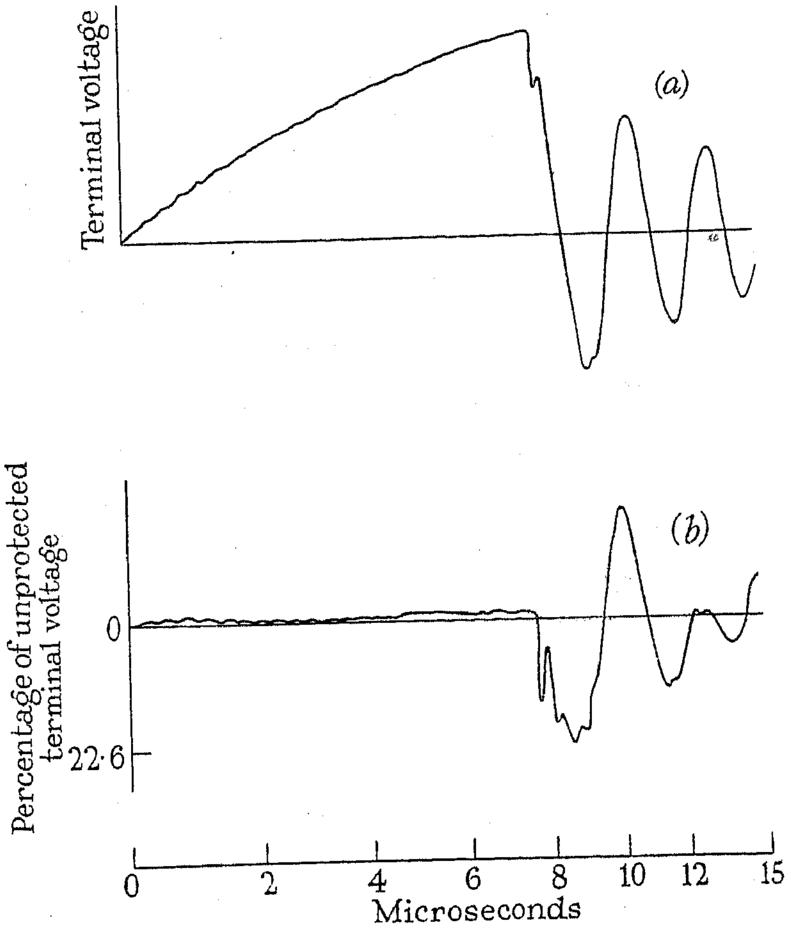

Fig. 21.—Voltages at the terminal and in the winding of No. 1 transformer, due to flashover on the front of a 5/40 travelling wave, when protected by a 6 000-$\mu\mu$F condenser. $Z_1 = 350$ ohms.

(*a*) Terminal voltage to same voltage scale as Fig. 18(*b*).
(*b*) Intercoil voltage to same voltage scale as Fig. 18(*d*).

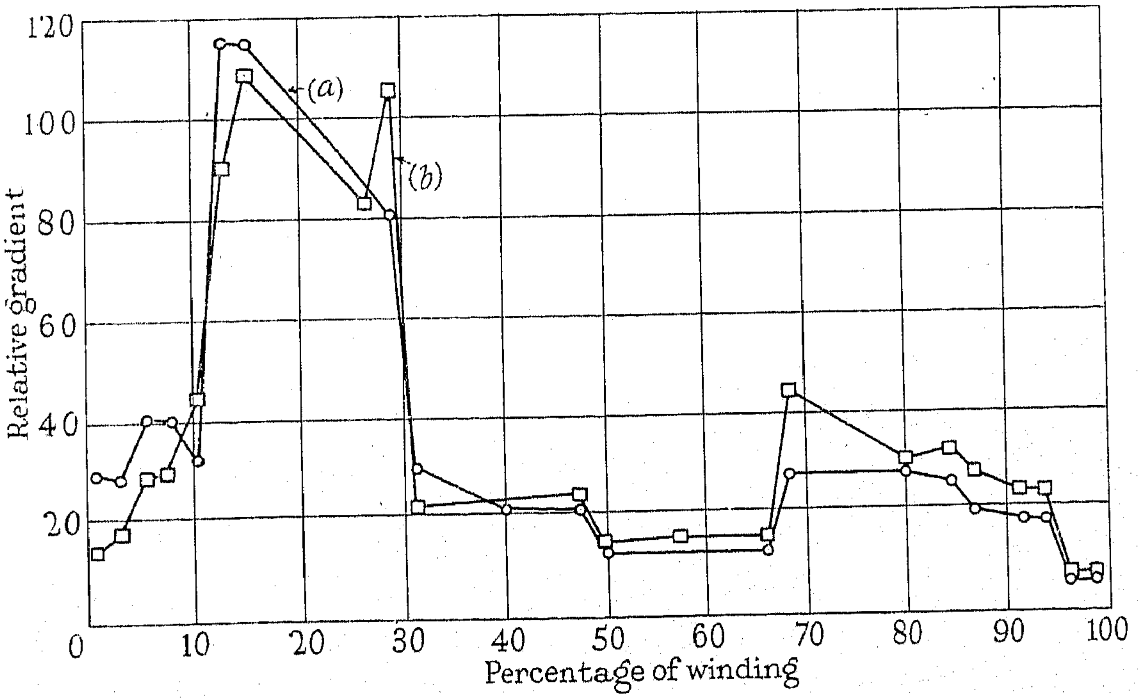

Fig. 22.—Relative intercoil gradients in No. 1 transformer winding, due to flashover on the front of a 5/40 travelling wave, (*a*) when protected by a 1 170-$\mu\mu$F condenser, and (*b*) when protected by a 6 000-$\mu\mu$F condenser. Assumed impulse ratio = 1·3.

The objection to the use of inductance coils, however, is the fact that by oscillating with the transformer capacitance they cause a rise of voltage at the transformer terminal, so that there is considerable danger of a flashover at this point. The phenomenon is illustrated in Fig. 23. Trace (*a*) is the voltage at a transformer terminal without an inductance, and (*b*) is the oscillatory voltage occurring with the inductance in circuit. Trace (*c*) shows the voltage when flashover occurs at the transformer terminal with the inductance in circuit. From its form it is evident that it will give rise to stresses in the transformer winding even greater than those shown in Fig. 18(*d*). For this reason the use of the inductance coil as a flattener is unsafe.

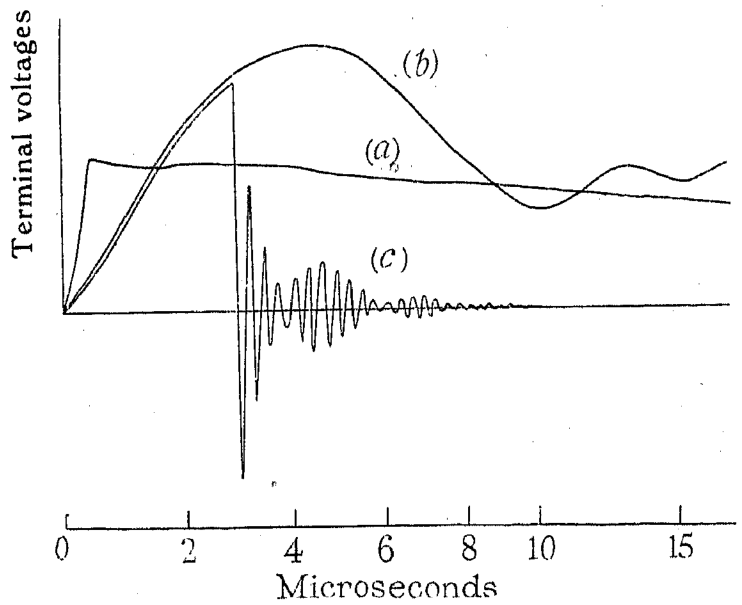

Fig. 23.—Voltages at the terminal of No. 1 transformer under 0·2/40 travelling-wave conditions. (*a*) when unprotected, and (*b*) when protected by an inductance. (*c*) shows the voltage when flashover, caused by the large voltage increase, occurs at the transformer terminal.

(*a*), (*b*), and (*c*) are all to same voltage scale.

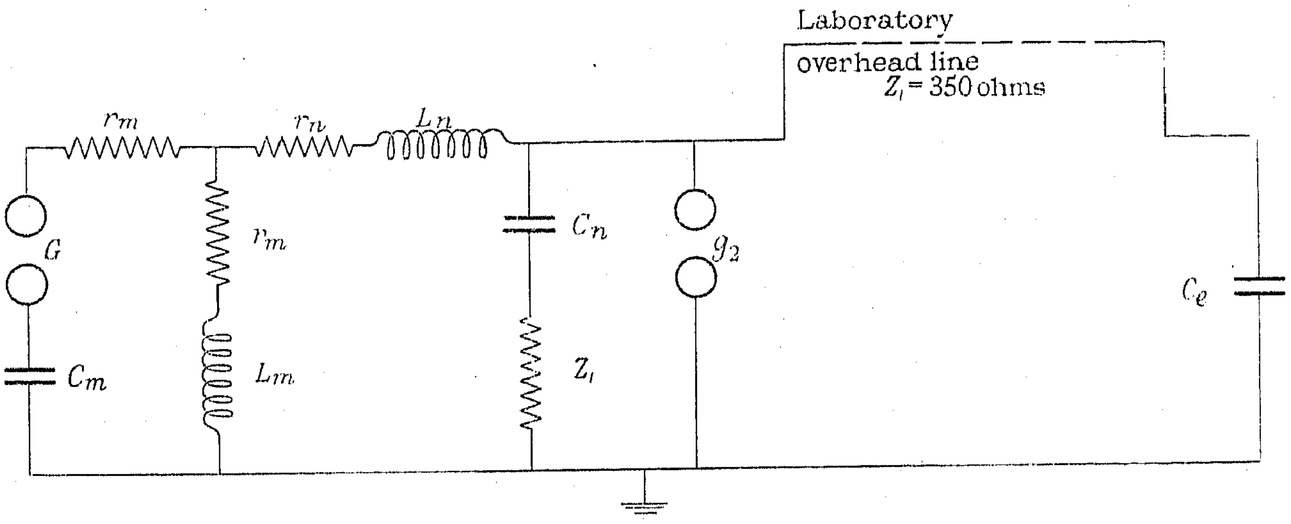

Fig. 24.—Circuit for simulating a travelling-wave flashover a short distance from a transformer, and not at the transformer as in Fig. 7. Characteristic impedance of surge generator = 350 ohms. Length of line is of the order of 1 span of an actual line.

(ii*d*) *Between-turn Voltages.*

Dealing generally with the voltages between turns for the case of the chopped wave, it was found that the stresses were a little greater than those occurring with the 0·2/40 travelling wave, just as the stresses between sections are greater. In the most highly stressed section in the winding it was found that the voltage between the most highly stressed turns was reduced to 24 % of its original value by the employment of the surge absorber. The condensers gave no reduction. The voltage distribution for the stresses between the first two turns of each section closely followed the distribution shown in Fig. 13.

(iii) Flashovers a short distance away from the transformer.

So far the condition of flashover somewhere near the transformer has been dealt with; but in some cases worse conditions may arise. This is where the flashover occurs across a co-ordinating gap or an insulator situated at a distance from the transformer less than that corresponding approximately to half the duration of the wave to half crest value. In such cases flashover will be accompanied by the incidence at the transformer of a wave from the temporary earth at the gap of opposite polarity to that of the incident wave. Thus, while the maximum voltage to earth at the transformer terminal will still be only of the order of twice the incident voltage, so far as voltage change is concerned the winding will be subjected to a steep wave-tail of the order of twice that due to a local flashover. This effect has been recorded on transmission lines with artificial travelling waves.* The condition is readily simulated in the laboratory by connecting between the surge generator and the transformer a length of transmission line of surge impedance equal to the characteristic impedance of the generator and allowing flashover to occur at the sending end. The circuit is shown in Fig. 24.

For a steep-fronted long-backed incoming wave [the use of a faster fronted wave here as opposed to that used in Sub-section (ii) does not in this case affect the distribution much] the voltage at the gap g_2 is shown in Fig. 25; it will be seen that flashover is occurring about on the middle of the front of the return reflection from the transformer. Under these circumstances the transformer terminal voltage is shown in Fig. 26(*a*). The greatly improved form of the terminal voltage with the surge absorber in circuit is shown in Fig. 26(*b*), while the voltages across a pair of coils due to the two voltages given in Figs. 26(*a*) and 26(*b*) are shown respectively in Figs. 26(*c*) and 26(*d*).

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* See Bibliography, (44).

The corresponding distribution curves are shown in Figs. 27 (*a* and *b*). There it will be seen that the gradients in the case of the unprotected transformer are greater than any of those previously discussed. With the surge absorber, however, there is the same levelling of the maximum stress as with the 0·2/40 wave.

The condenser as a means of protection is more satisfactory here than in the case of flashover near the transformer. The reason for this, of course, is that the frequency or rate-of-change of voltage in the oscillation round the local circuit is much less than in the previous case, because the length of line between the transformer and the point of flashover is now very much longer.

The terminal voltages for 6 000-$\mu\mu$F and 0·042-μF condensers are shown respectively in Fig. 28 (*a* and *b*), and the two distribution curves corresponding to these are given in Fig. 27 (*c* and *d*). Comparison is possible here for the 6 000-$\mu\mu$F condenser, and it is seen that it reduces the maximum gradients to something of the order of twice the value that was obtained for the same condenser under the 0·2/40 travelling-wave conditions.

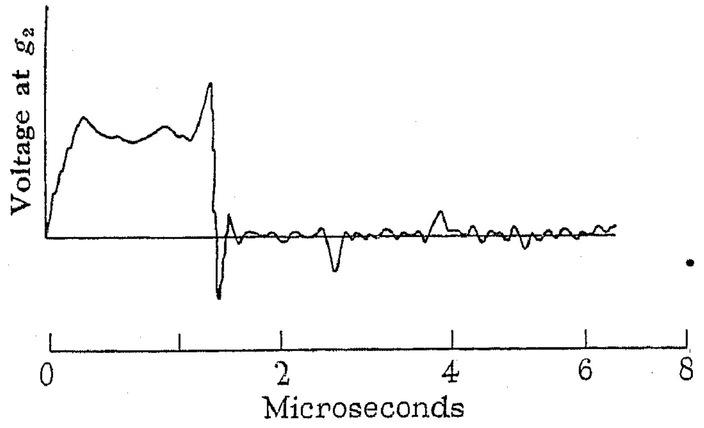

Fig. 25.—Voltage at a gap one span-length from a transformer (as shown in Fig. 24), due to flashover on the front of the first return reflection to the gap. 0·3/40 incident wave.

The same kind of distribution curves as in Fig. 27 were obtained when flashover occurred either at the bottom or the top of the front of the return reflection, and also when slow-fronted waves were used.

The same phenomena occur, of course, when there is a short length of cable between an overhead line and a transformer. While the cable flattens the incoming wave-fronts into a series of steps by virtue of the to-and-fro reflections in it, a flashover at the cable-line junction across the pot-head gives rise to rapid voltage reversals at the transformer.

(e) Direct Lightning Strokes at or near the Transformer.

(i) General consideration of the simulating circuits.

This Section deals with the transient conditions arising from strokes connecting with the line in such close proximity to a transformer that the latter is not subjected to fully formed waves. Both methods of incidence of lightning surges into the transmission system are here contemplated, i.e. (ii) a direct lightning stroke to a line conductor with subsequent flashover of one or more insulators towards earth, and (iii) a lightning stroke to a transmission tower or earth-wire system with subsequent flashover to a line conductor.

The corresponding transformer impulse-testing arrangements therefore require to simulate the amplitudes, rates of rise, and durations, of over-voltages which can reach the transformer terminal under these conditions, and these factors are a direct consequence of the transient-voltage conditions which arise between the line and the earth plane close to the stricken point. Several factors, some as yet only speculatively determinate, control these

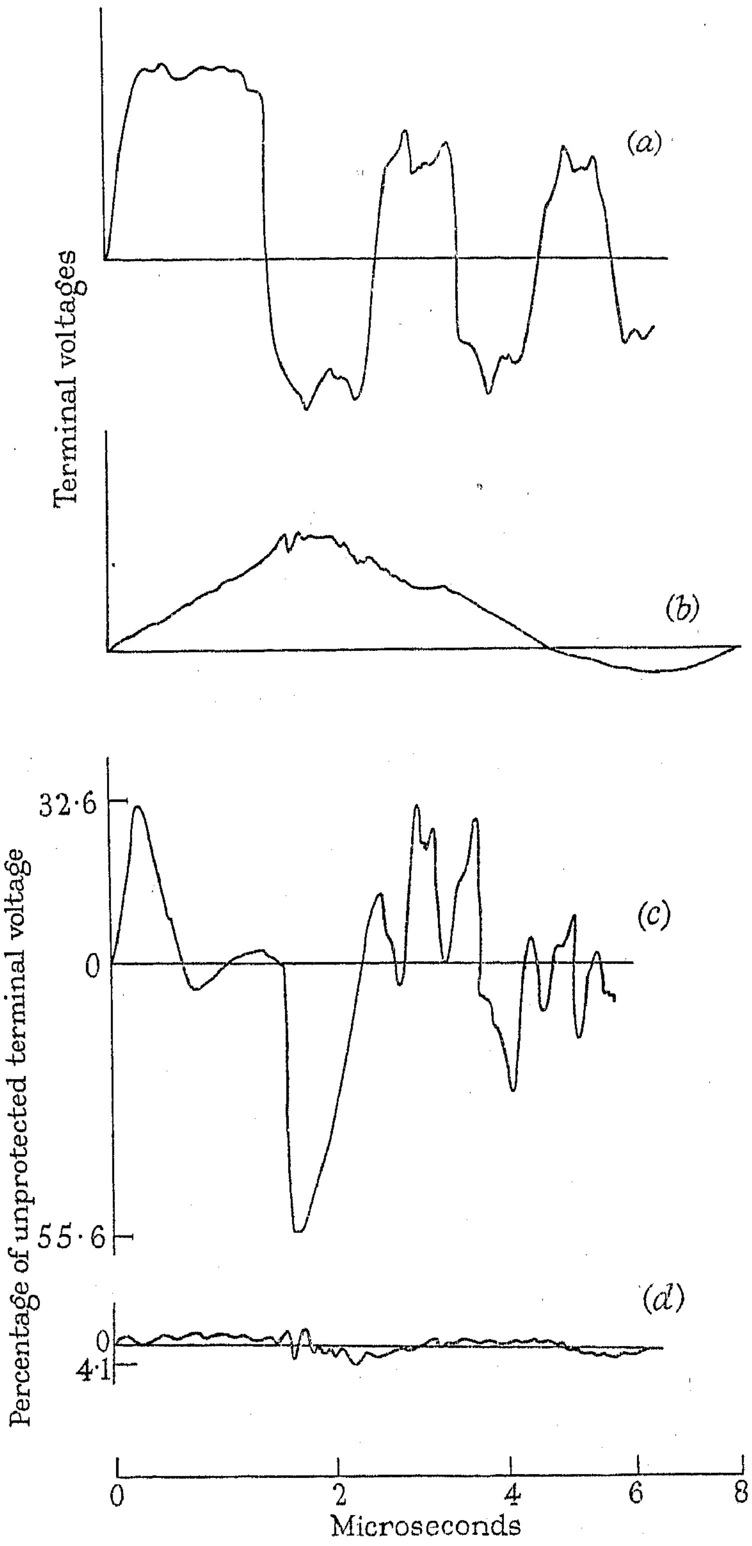

Fig. 26.—Terminal and intercoil voltages for No. 1 transformer, due to flashover on the front of a 0·3/40 travelling wave at a gap one span-length from the transformer. $Z_1 = 350$ ohms.

(*a*) Terminal voltage, unprotected.
(*b*) Terminal voltage, protected by the surge absorber.
(*c*) Intercoil voltage, unprotected and corresponding to terminal voltage (*a*).
(*d*) Intercoil voltage, protected by the surge absorber and corresponding to terminal voltage (*b*).

(*a*) and (*b*) are to same voltage scale as Fig. 25.
(*d*) is to same voltage scale as (*c*).

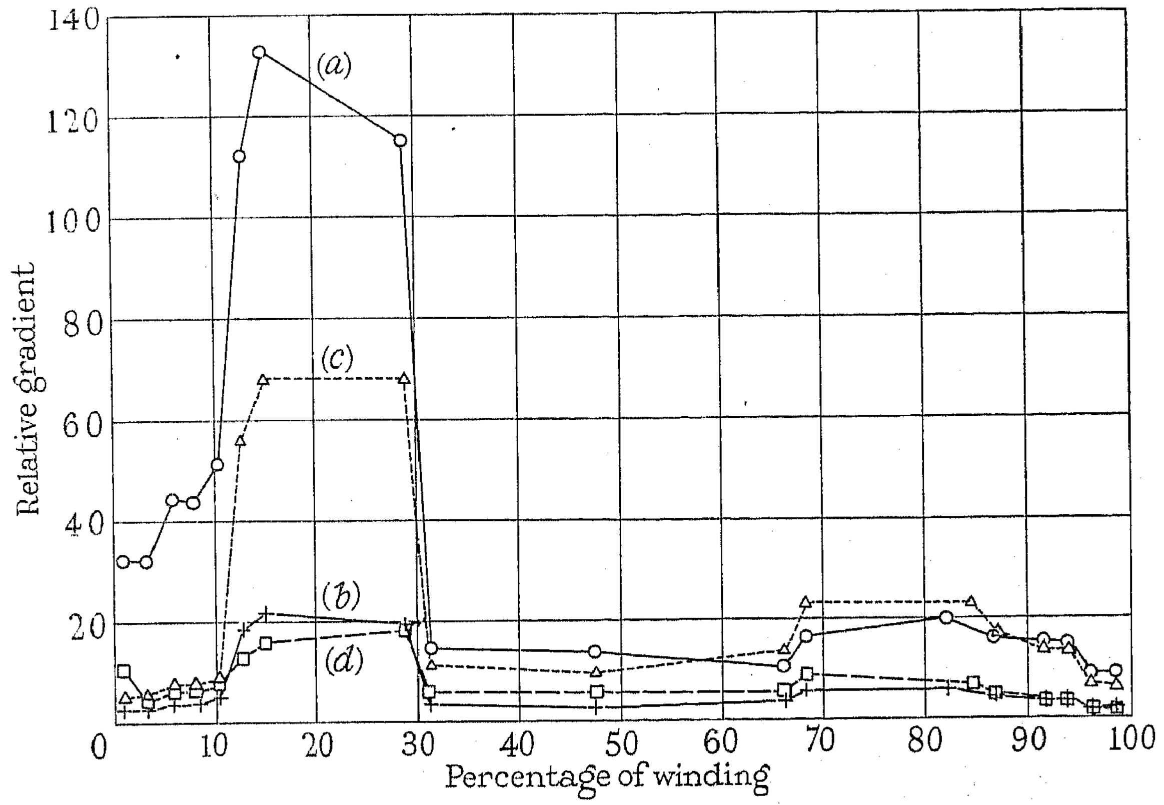

Fig. 27.—Relative intercoil gradients in No. 1 transformer winding, due to flashover on the front of a 0·3/40 travelling wave at a gap one span-length from the transformer, when (*a*) unprotected, (*b*) protected by a surge absorber, (*c*) protected by a 6 000-$\mu\mu$F condenser, (*d*) protected by a 42 000-$\mu\mu$F condenser.

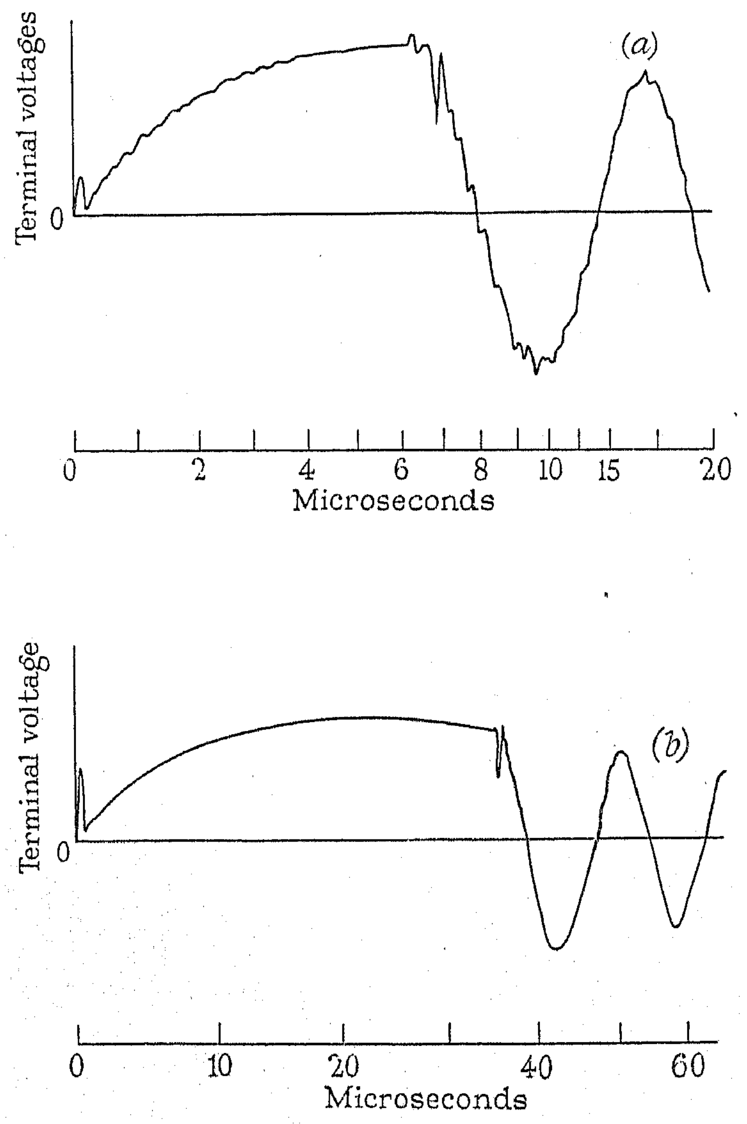

Fig. 28.—Terminal voltages for No. 1 transformer, due to flashover on the front of a 0·3/40 travelling wave at a gap one span-length from the transformer, when (*a*) protected by a 6 000-$\mu\mu$F condenser, (*b*) protected by a 42 000-$\mu\mu$F condenser.

(*a*) and (*b*) are to same voltage scale as Fig. 25.

conditions. Thus maximum lightning-stroke voltage, rate of rise of voltage, stroke current, lightning-stroke surge impedance, tower-earth resistance, line surge impedance, and impulse flashover characteristics of insulators, are all relevant. Available data suggest, as common, stroke voltages of the order of 10 to 20 megavolts, rates of rise of 5 megavolts per microsecond, and currents at least of the order of 40 000 amperes, while the stroke surge-impedance effect is of the order of 250 ohms, the line surge impedance is of the order of 400 ohms, and tower-earth resistances of 2 to 50 ohms are usual.

On the basis of these data it is clear that, under condition (ii) of a direct stroke to the line conductor, the actual maximum stroke voltage is only of importance in so far as it ensures that insulator flashover will be reached on all voltages of transmission line, since the surge voltage in the line will not rise above the flashover value of the insulator in any event. It is also clear that in all these cases flashover is likely to occur in a time less than a microsecond from the effective commencement of voltage-rise, and, so far as the data permit, the authors conclude that an effective time to flashover of the order of 0·25 microsecond is typical,* for which the insulator impulse ratio is of the order of 5·0. Also, under this condition, so long as the tower earth resistance is low it is clear that it does not greatly affect the nature of the dangerous overvoltage on the line.

Under condition (iii) of a stroke to a transmission tower, it is clear that the tower-earth resistance and the

* For the most common lightning strokes, Goodlet [see Bibliography, (37)] quotes data which correspond to 5 megavolts per microsec. average rate of rise to a maximum of 10 megavolts at 2·0 microsec. Probably up to 3 megavolts the rate of rise may be about double this; i.e. 10 megavolts per microsec. Assuming 250 ohms stroke impedance and 400 ohms line impedance, the corresponding figures on a stricken line would be some 4·5 megavolts per microsec. up to 1·3 megavolts. Under these conditions we should expect flashover of a 66-kV line insulator at about 1·2 megavolts after a time of, say, 0·2 to 0·25 microsec. where the impulse ratio may be some 5·0 [*ibid.*, (38)]. It is clear that, on lines operating at voltages higher than 66 kV, conditions from the point of view of relative amplitude and wave-front of the voltage at the stricken point will not be so severe, but on the medium- and lower-voltage lines matters will be much worse.

earth-wire surge impedance[*] in conjunction with the stroke surge impedance and the maximum available lightning-stroke voltage, together determine whether or no flashover will occur. In the same way the earth resistance and the stroke impedance reduce considerably the rate of rise of voltage on the tower top, so that when flashover does occur it will be longer delayed and the insulator impulse ratio will be lower than in the previous case. The authors have here taken a time to flashover of 1·5 microsec. as typical, for which the impulse ratio is some 2·0 times. It is clear also that in this case the duration of the dangerous voltage on the line is determined more largely by the tower-earth resistance.

Having indicated that the actual potentially available lightning-stroke voltage and current only matter in so far as they determine the nature and magnitude of the overvoltage on the line, it will be clear that when obtaining the information necessary to estimate the comparative strength of a transformer, and when investigating the form of the terminal voltages arising, it is not necessary to carry out tests under completely simulated lightning conditions. On this account a conveniently low test voltage can be used so long as the estimated times to flashover are observed and so long as the circuits employed simulate those factors presumed to be important in practice. Thus in the tests a surge generator of suitable output voltage and having a surge impedance characteristic discharged into the No. 1 transformer via circuits which represented tower-earth resistances, line surge impedances, both concentrated and distributed, and insulator flashovers. The rate of rise of the generator voltage was adjusted so as to give flashover of the small-scale insulator gaps in the times decided typical for the assumed full-scale conditions. In presenting the data the transformer gradient distribution curves were, as stated, corrected for the impulse ratios expected under real conditions.[*]

(ii) Direct strokes to a line at or near a transformer. Three practical cases are simulated.

(ii*a*) *Stroke to a Conductor near a Transformer Terminal with Flashover both at this Terminal and at the First Tower.*

This condition[†] is shown in Fig. 29(*a*) and the testing circuit to simulate it is shown in Fig. 29(*b*). The surge generator, having a characteristic surge impedance of 350 ohms,[‡] discharges directly on to the transformer C_e. The latter is connected to the laboratory line[§] ($Z_1 = 350$ ohms) representing one span-length of conductor, which terminates in a resistance $R_1 = 350$ ohms, representing the continuance of the line. The gaps g_1 and g_2 represent respectively the insulator flashovers at "f" and "h."[||]

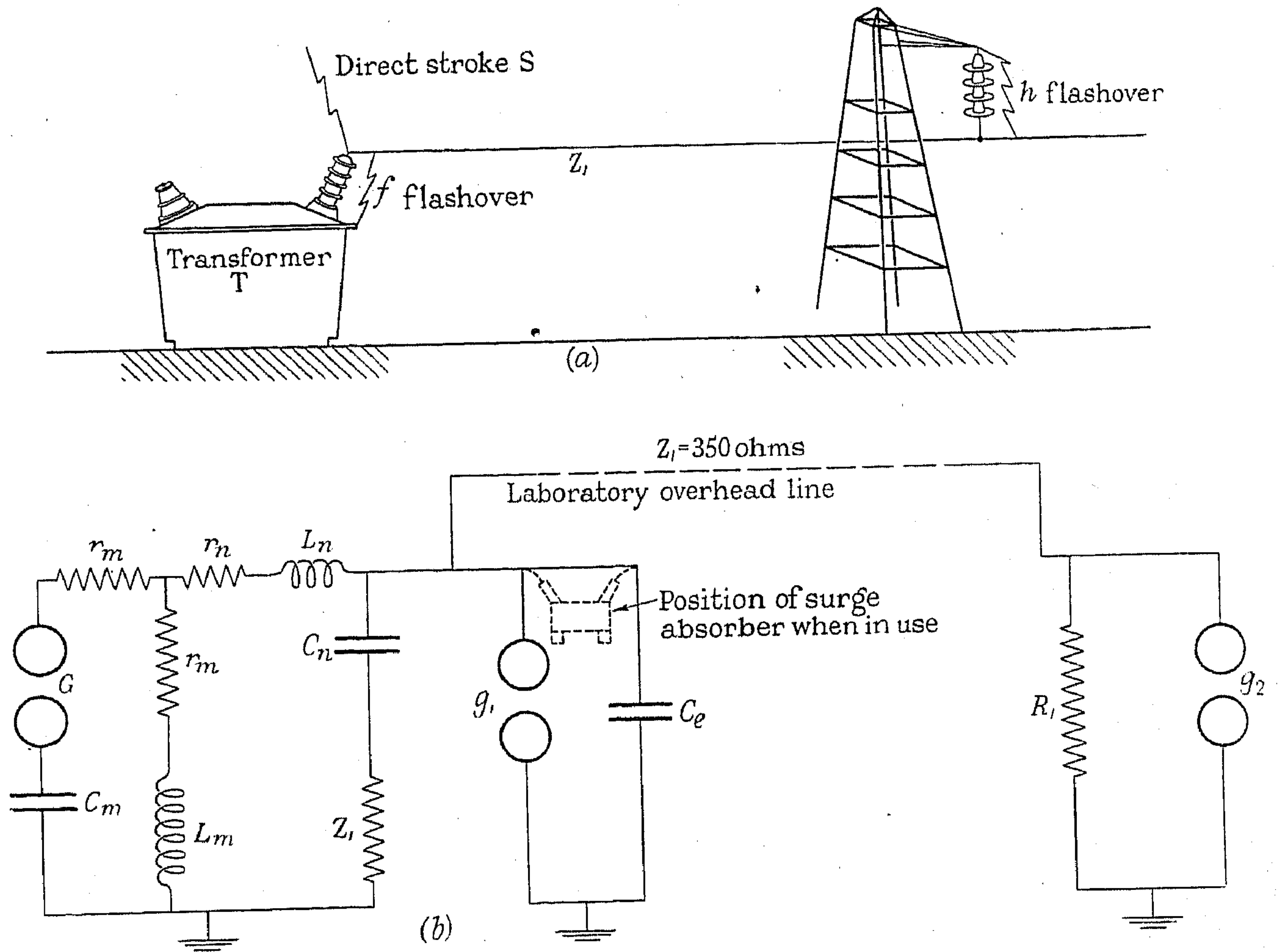

Fig. 29.—Circuit to simulate a direct stroke to the line at the transformer, which causes flashovers at the transformer terminal "f" and at the line insulators "h," one span-length away.

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[*] The fact that the surge impedance of a high tower might control flashover with strokes having rapid rates of voltage increase must not be set aside [see Bibliography (39)].

[*] As before, in Sub-section (ii), equal impulse ratios—in this case 5—have been taken for the unprotected and surge-absorber-protected cases. For the condensers lower figures have been employed which are stated on the curves.

[†] Actually operating records show that a large number of strokes to systems either with or without earth wires are accompanied by flashover on more than one insulator assembly in one phase [see Bibliography, (40)].

[‡] Perhaps 250 ohms would have been a more average surge impedance, but 350 ohms has been used because it was available and because the overhead line had this impedance. It has already been made clear that the performance of the surge absorber is little affected by the surge impedance of the source.

[§] Of the order of 1 000 ft. in length.

[||] The levels of insulation at "f" and "h" have been taken as equal.

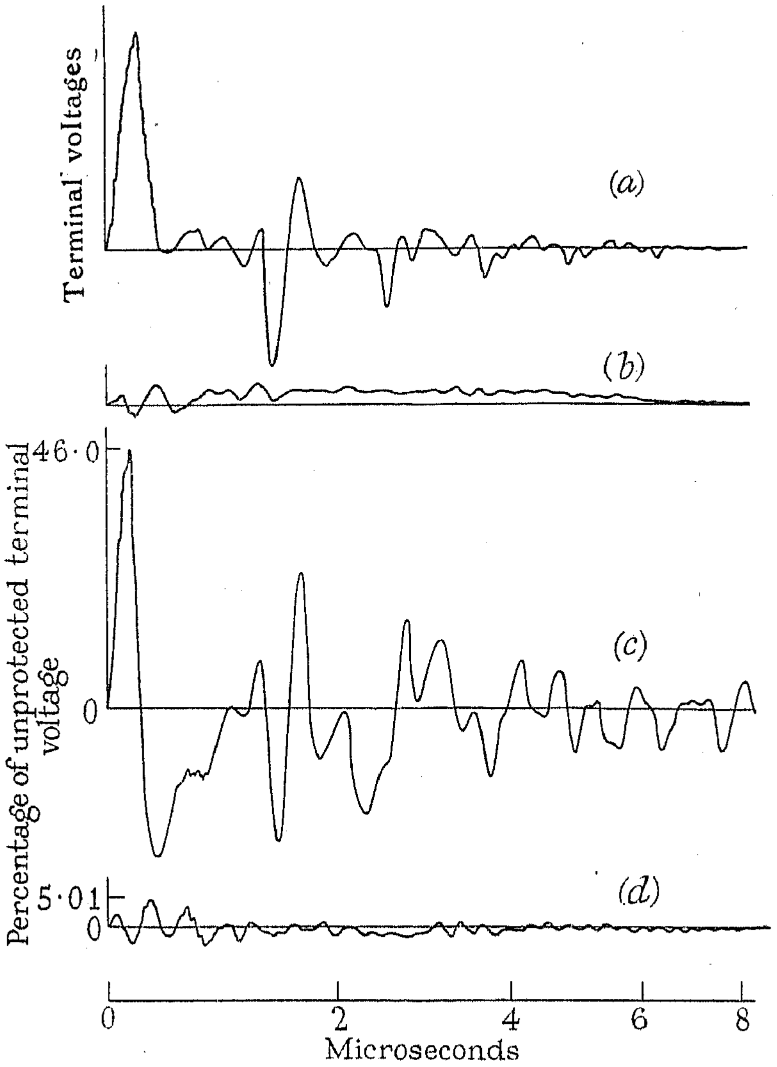

Fig. 30.—Terminal and intercoil voltages for No. 1 transformer under direct-stroke conditions as given in Fig. 29(*b*), with flashover at about 0·25 microsec.

(*a*) Terminal voltage, unprotected.
(*b*) Terminal voltage, protected by the surge absorber.
(*c*) Intercoil voltage, unprotected, corresponding to terminal voltage (*a*).
(*d*) Intercoil voltage, protected by the surge absorber, corresponding to termina voltage (*b*).
(*a*) and (*b*) to the same voltage scale.
(*c*) and (*d*) to the same voltage scale.

The double flashover gives the terminal voltages shown in Fig. 30(*a*), where the reflections between g_1 and g_2 are evident. The applied voltages are so short in duration that the surge absorber is able to give a marked reduction in voltage amplitude, as shown in Fig. 30(*b*); this, of course, is an important characteristic since it must be remembered that in practice the unprotected transformer terminal-voltage amplitude here is very much greater than that arising with travelling waves.

The intercoil voltages are shown in Fig. 30(*c* and *d*). The terminal-voltage tail in the unprotected case is steeper than the front, and therefore the corresponding total negative deflection of the intercoil voltage is greater than the positive deflection due to the front. Since, however, the negative or downward deflection commences where the positive one finishes, the net result is that the maximum stress here is occasioned by the front. Lower down in the winding the reverse case holds.

The gradient curves are shown in Fig. 31. It will now be noticed that the line-end gradient in the unprotected case is, first, almost as great as that lower down in the winding, and, secondly, very much greater than that occurring with the travelling waves. This is caused by the short duration of the applied wave, which prevents penetration into the winding, and by the fact that the voltage amplitude is 3·8 times greater, due to differing impulse ratios, than that used in deriving, for instance, Fig. 9. It will thus be seen that, with the existing reinforcement on this winding, breakdown might now occur at the line end of the winding.

The condenser terminal voltages (condensers of 6 000 $\mu\mu$F and 0·042 μF were employed) exhibited the same characteristics as in Section 5(*d*)(ii*b*), with the result that the corresponding gradient curves were quite unsatisfactory, despite the fact that lower impulse ratios were used with the condensers. Actually, the longer duration of the terminal voltage with the condenser in circuit allowed of deeper penetration into the winding. This effect, combined with the fact that the voltage is oscil-

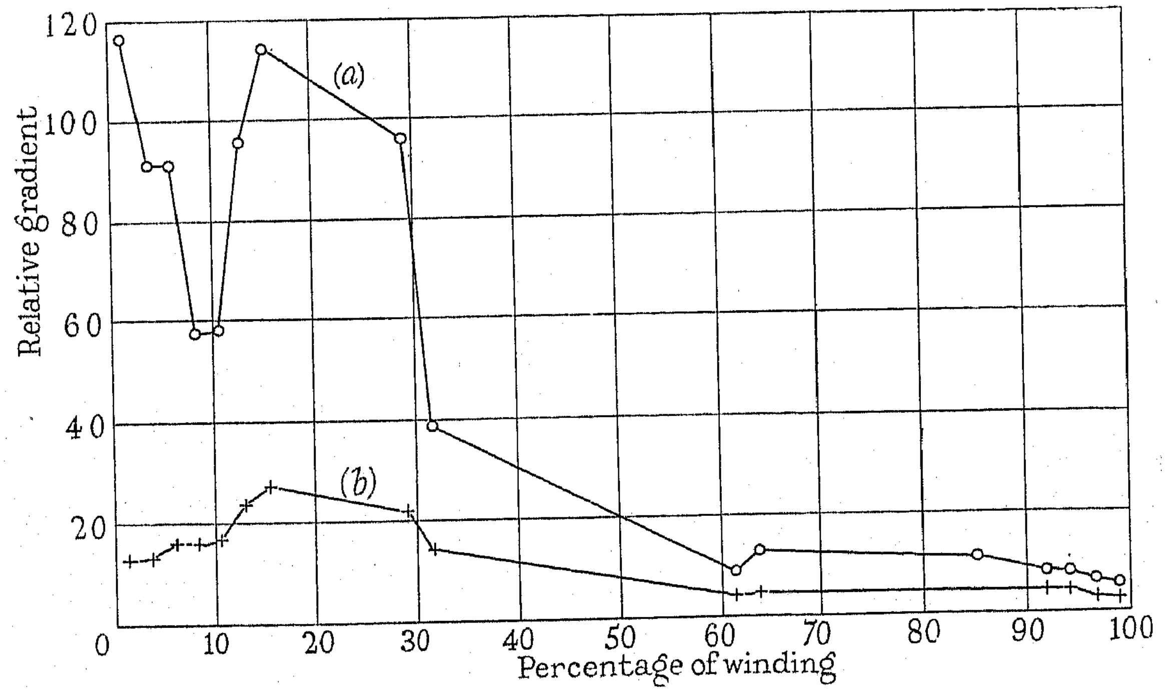

Fig. 31.—Relative intercoil gradients in No. 1 transformer winding under the direct-stroke conditions given in Fig. 29(*b*), with flashover at about 0·25 microsec., when (*a*) unprotected, (*b*) protected by the surge absorber. The assumed impulse ratios are 5·0 in both cases.

latory, gave rise to gradients in the 10—30 % range of the winding of the same order as those obtained in the unprotected case. Typical oscillograms are in Fig. 32.

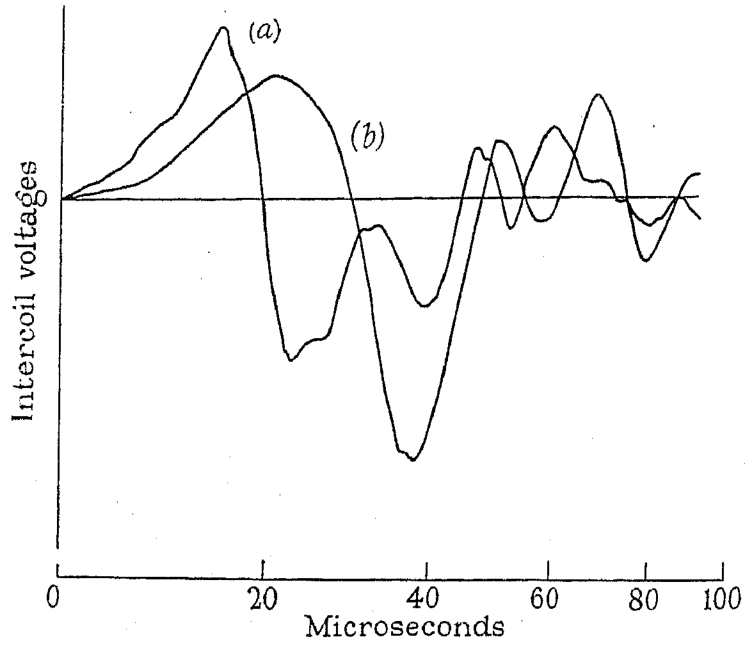

Fig. 32.—Intercoil voltages at a point near the middle of No. 1 transformer winding under direct-stroke conditions as given in Fig. 30(*a*), (*a*) when unprotected, and (*b*) when protected by a 6 000-$\mu\mu$F condenser.

It will be realized also that if flashover of g_1 occurs at, say, 1 instead of 0·25 microsec. (as it might with very high-voltage lines or with very slow-fronted strokes) the whole character of the distribution shown in Fig. 31 is altered. The reason for this is that the longer time to flashover involves a lower impulse ratio in the unprotected and surge-absorber-protected cases than before, and, in addition, the longer terminal wave obtained allows deeper penetration into the winding, so that compared with Fig. 31 the relative gradient for the unprotected transformer is reduced to 32 at the line end and practically unaffected in the 10–30 % range of the winding, while here the gradient with the 6 000-$\mu\mu$F condenser reaches a value of 140. The surge-absorber gradient curve is essentially unaltered. The terminal voltages for such a condition are shown in Fig. 33.

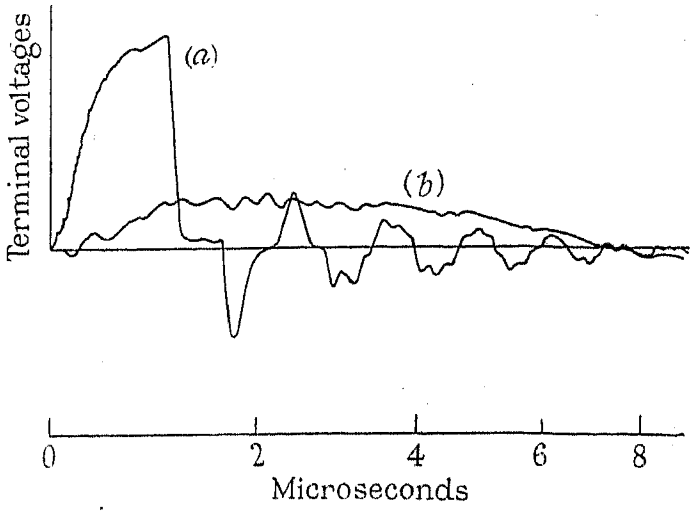

Fig. 33.—Voltages at the terminal of No. 1 transformer under direct-stroke conditions given in Fig. 29(*b*), with flashover at about 1·0 microsec., (*a*) when unprotected, (*b*) when protected by the surge absorber.

(*a*) and (*b*) are to same voltage scale.

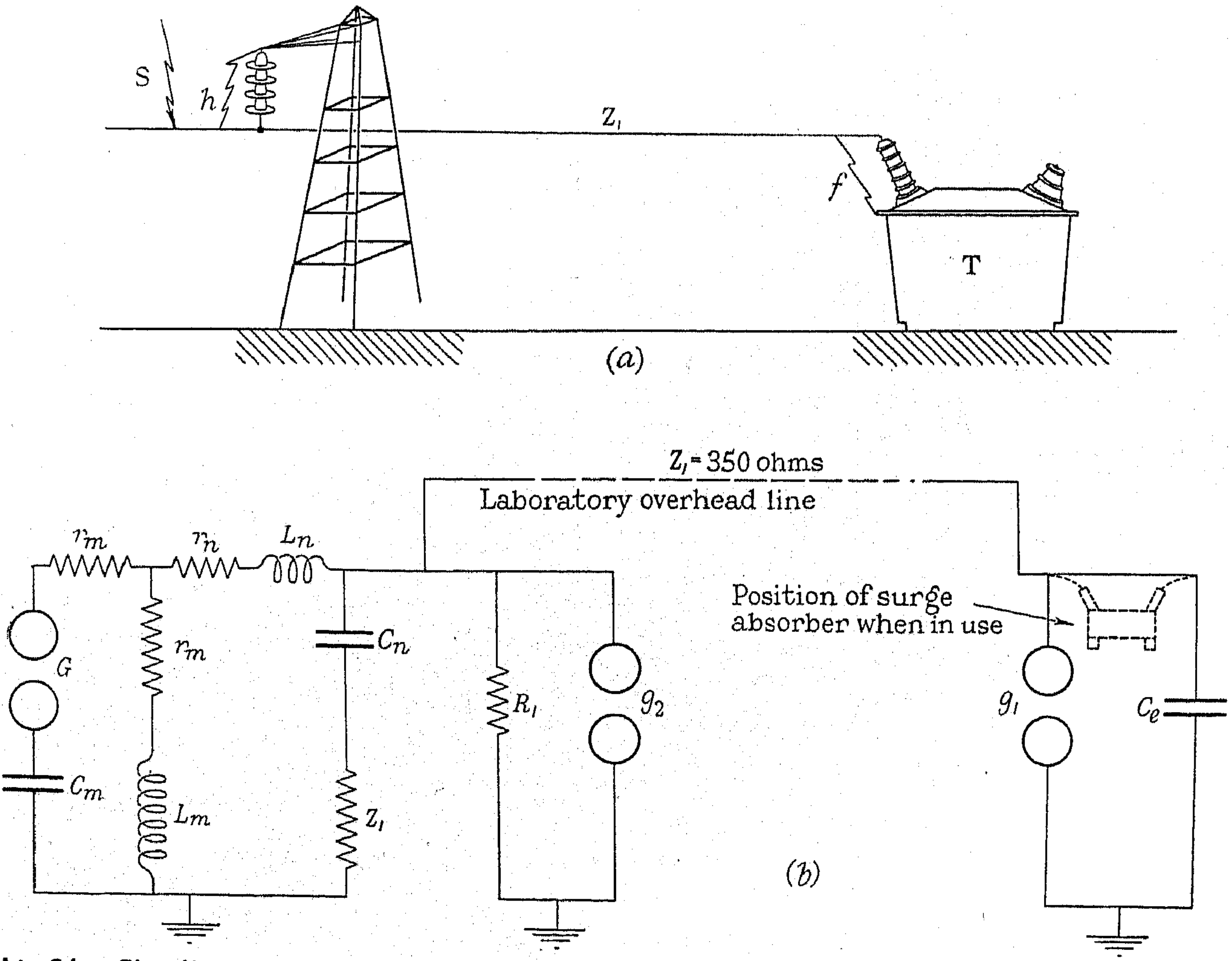

Fig. 34.—Circuit to simulate a direct stroke to a line one span-length from the transformer, which causes flashovers at the line insulators " h " and at the transformer terminal " f."

(ii*b*) *Stroke to a Conductor near a Transformer Terminal with Flashover only at this Terminal.*

When there is only a flashover at the transformer terminal, to simulate the condition, R_1 in Fig. 29(*b*) is connected directly across C_e, and the line and g_2 are removed. Despite the absence of reflections the distribution curves differ little from those given in Fig. 31.

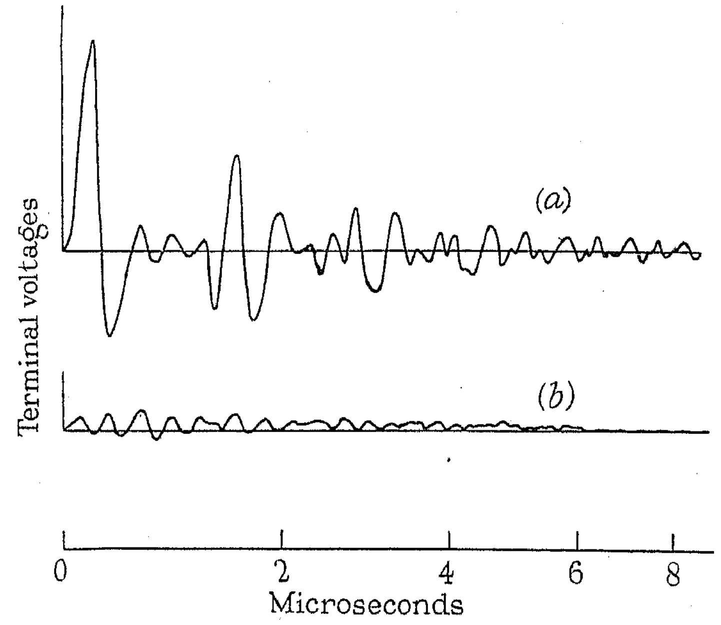

Fig. 35.—Voltages at the terminal of No. 1 transformer under direct-stroke conditions as given in Fig. 34(*b*), with flashover at about 0·25 microsec., (*a*) when unprotected, (*b*) when protected by surge absorber.

(*a*) and (*b*) are both to same voltage scale.

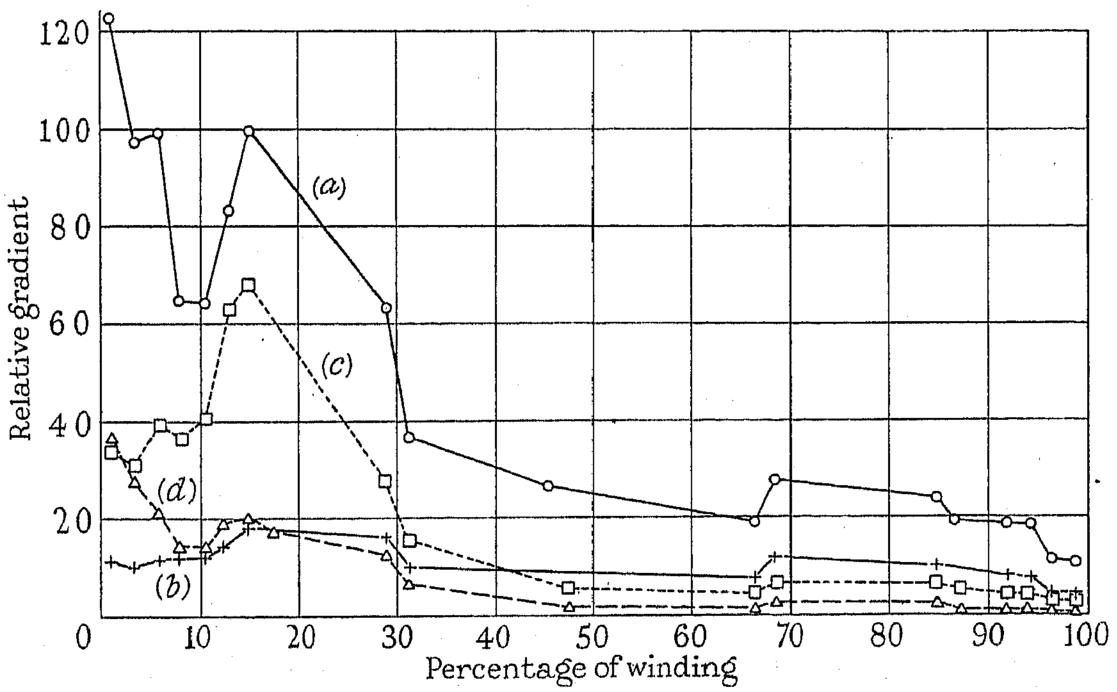

Fig. 36.—Relative intercoil gradients in No. 1 transformer winding under the direct-stroke conditions given in Fig. 34(*b*), with flashover at about 0·25 microsec., (*a*) when unprotected, (*b*) when protected by the surge absorber, (*c*) when protected by a 6 000-$\mu\mu$F condenser, (*d*) when protected by a 42 000-$\mu\mu$F condenser. The assumed impulse ratios are respectively, for curve (*a*) 5·0, for curve (*b*) 5·0, for curve (*c*) 2·0, and for curve (*d*) 1·5.

(ii*c*) *Stroke to a Conductor at the First Tower with Flashover both at this Tower and at the Transformer Terminal.*

The conditions are illustrated in Fig. 34(*a*) and the circuit to simulate them in Fig. 34(*b*). Under these conditions the short wave incident from "h" is chopped at "f," with the result that the transformer receives a wave of very short duration* (shown in Fig. 35). The steepness of this wave results in large gradients at the line end of the transformer winding despite the heavy reinforcement here, but it is short enough to give smaller gradients lower down in the winding. As is shown in the distribution curves (Fig. 36), this also applies for the 6 000-$\mu\mu$F and 0·042-μF condensers.

(iii) Direct strokes connecting with the line via a tower-to-line flashover near a transformer.

The practical case with two flashovers is illustrated in Fig. 37(*a*) and the circuit simulating the condition in Fig. 37(*b*). R_T now represents the tower-foot earth resistance, R_1 the surge impedance of the long length of line to the left of "h" in Fig. 37(*a*), and the laboratory line the short length of conductor between "h" and "f." As pointed out earlier, the surge generator was set to give a front of about 1·5 microseconds, but the other circuit connections are such that the voltage at P is steeper than this.†

With various values of R_T and relative settings of the gaps g_1 and g_3 it was found that there was not much change in the transformer terminal voltages, and also that these voltages were longer in duration than those in Section (ii), owing to the fact that flashover occurred nearer the maximum of a slower front. Again, the distribution curves for the 6 000-$\mu\mu$F and 0·042-μF condensers were quite unsatisfactory, while those for the unprotected and surge-absorber-protected cases were somewhat lower than in Sub-section (ii). This is to be expected, since in practice a smaller value of the impulse ratio would exist. In low-voltage systems, or with very high tower-earth resistances, where flashover would

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* A slightly lower level of insulation near the transformer than on the line is here assumed.

† Whether this phenomenon occurs in practice is not proven, but the suggestion has been put forward by one of the authors in explanation of the possibility of steep waves on lines being formed from slow-fronted strokes [see Bibliography, (41)].

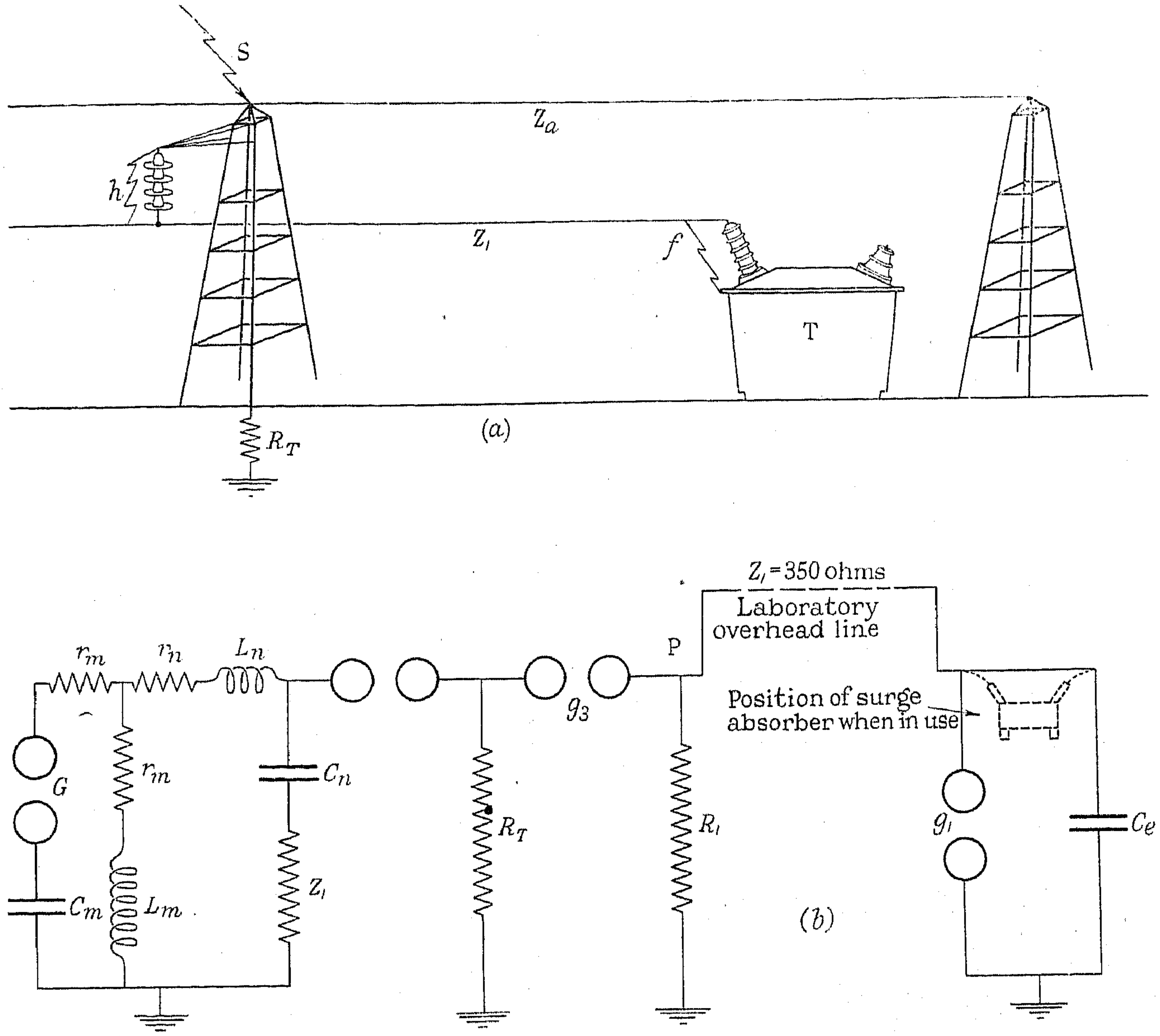

Fig. 37.—Circuit to simulate a direct stroke to a line via a tower-to-line flashover "h," one span-length from the transformer, causing a flashover "f" at the transformer terminal.

probably occur lower down on the tower-top voltage-front, the conditions arising will no doubt be just as severe as those arising in unguarded systems.

It will be appreciated, of course, that if there is no flashover at "f" in Fig. 37(*a*), then the voltage tail at the transformer will depend on the *RI* drop in the tower-earth resistance and may be long.

(f) Comparative Results on other Transformers.

The transformers here dealt with were tested under 0·2/40 travelling-wave conditions. In all cases they were complete with cores and l.t. windings. The measurements were made in air but the windings were surrounded by dummy tanks fixed at the appropriate distances from them.

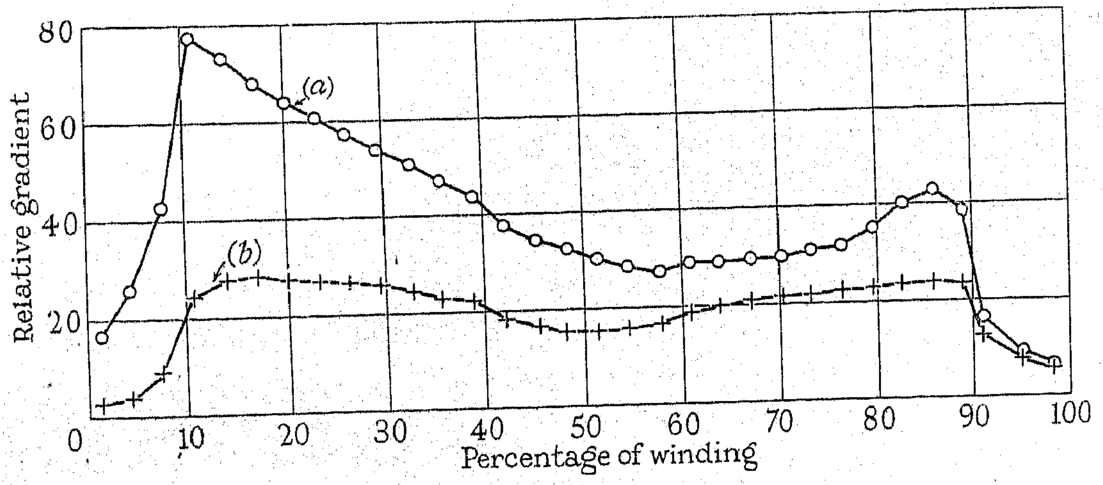

Fig. 38.—Relative intercoil gradients in the h.t. winding of No. 4 transformer under 0·2/40 travelling-wave conditions, (*a*) when unprotected, (*b*) when protected by the surge absorber.

(i) Single-phase transformer (No. 3) having no reinforcement and forming one phase of a 1 800-kVA, 33-kV star-connected bank operating at 33 kV, 50 cycles.

This transformer, having a rating of 1 800 kVA at 33 kV, and having no reinforcement, has already been considered. The distribution curves are shown in Fig. 11. As stated before, the value of α was 16·7 and the natural frequency 17 500 cycles per sec.

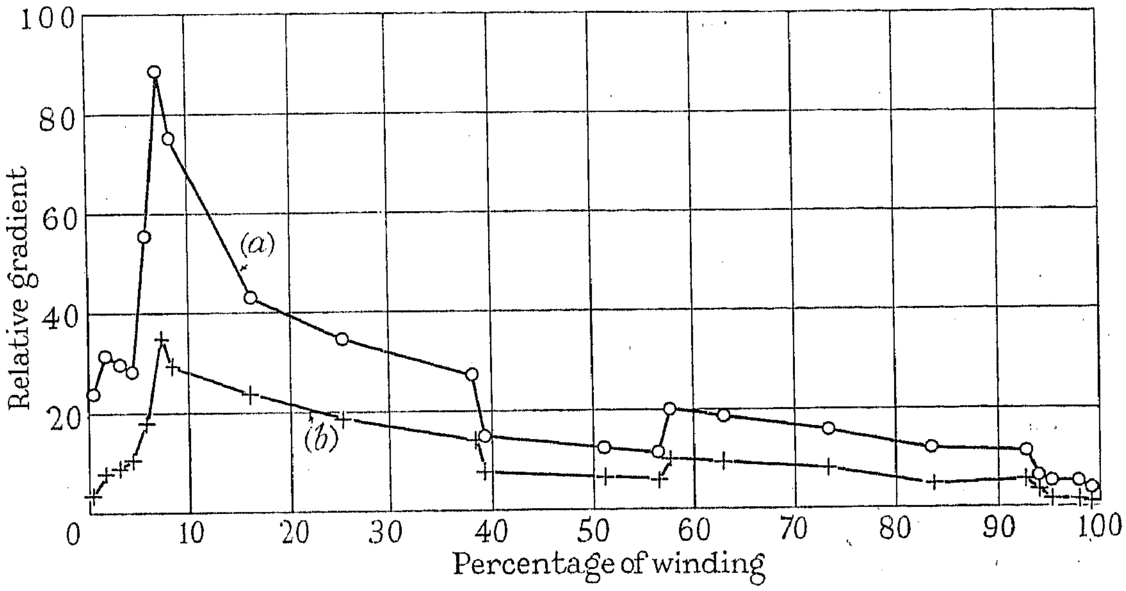

Fig. 39.—Relative intercoil gradients in the h.t. winding of No. 5 transformer under 0·2/40 travelling-wave conditions, (*a*) when unprotected, (*b*) when protected by the surge absorber.

(ii) Single-phase transformer (No. 4) forming one phase of a 45 000-kVA star-connected bank operating at 88 kV, 50 cycles.

This transformer had a natural frequency similar to that of the 37 500-kVA transformer—No. 1—but a much smaller value of α. These constants were respectively 39 000 cycles per sec. and 6·8. In addition, the insulation in the axial direction—designed in accordance with a British Standard Specification of fairly recent date—was such that to a 0·2/40 travelling wave it was relatively 30 % stronger than the No. 1 transformer. Its rating was 45 000 kVA, its line voltage 88 kV, it was wound with disc coils, and it was operated with one end of the winding earthed.

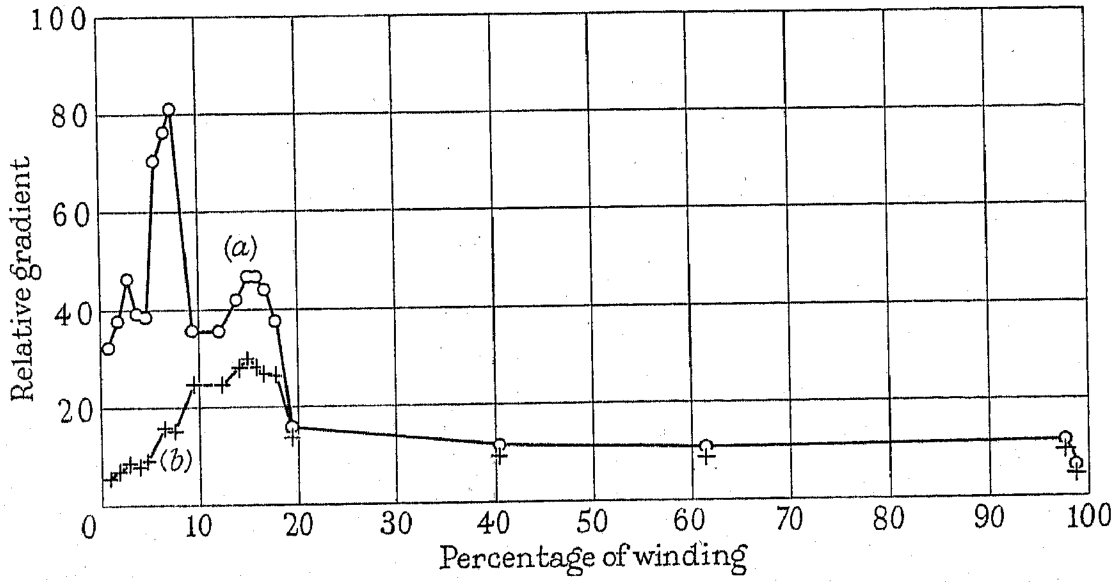

Fig. 40.—Relative intercoil gradients under 0·2/40 travelling-wave conditions in one h.t. phase of No. 6 transformer, (*a*) when unprotected, (*b*) when protected by surge absorber.

The voltage-distribution curve for the 0·2/40 travelling-wave condition for the unprotected and surge-absorber-protected cases is shown in Fig. 38. It will be seen that despite the low value of α the standard surge absorber—absorbers giving the same degree of flattening were used with transformers Nos. 1, 2, 3, 4, and 5—produces about the same level of gradient as with No. 1 transformer.

(iii) Single-phase transformer (No. 5) forming one phase of a 5 000-kVA 3-phase star-connected bank operating at 110 kV, 50 cycles.

The next transformer also had a rather low value of α, but its natural frequency was very much lower than those used hitherto. The value of α was 13 and the natural frequency 7 300 cycles per sec. It was an older design than the others and was very heavily reinforced in the tapping range. In the axial direction it was relatively about 12 % stronger than the 37 500-kVA transformer.

It was operated with an earthed neutral and also had disc windings.

The distribution curves for the 0·2/40 travelling-wave condition for the unprotected and the surge-absorber-protected cases are shown in Fig. 39. It is evident here that while there is only an increase in strength of 2·5 times, the surge absorber, despite the low natural frequency of the winding and the low value of α, produces a gradient level only a little greater than that obtained with the higher-α, higher-natural-frequency, No. 1 transformer.

(iv) 3-phase delta-connected transformer (No. 6) of 100 kVA, 6·6 kV, 50 cycles, having single-wire multi-layer coils.

The last transformer was a 100-kVA, 6·6-kV, 3-phase, delta-connected transformer, insulated in accordance with standard specifications. Measurements were made in this case between pairs of layers, and the tests were carried out with the h.t. line terminals earthed through 350 ohms to simulate the lines which would be connected in practice. The value of its natural frequency was 25 000 cycles per sec. The distribution curves for the 0·2/40 travelling waves for the unprotected and surge-absorber-protected cases are shown in Fig. 40, and it is seen that the surge absorber used here (it gave only 65 % of the flattening obtained with the absorbers used with the other five transformers) increases the winding strength by a factor of 2·7.

An interesting observation is that the distribution curves with this multi-layer coil winding are similar in shape to those obtained with the disc coil windings, the maximum gradients occurring near, but not at, the line end. This similarity is the more interesting when it is remembered that the present windings are delta-connected. Actually a set of distribution curves were obtained on the winding both without and with the surge absorber in circuit for the other two cases of a star connection with an earthed neutral and a floating neutral, but it was found that not only was there practically no difference between the maximum gradients for the three cases but also that there was inappreciable difference between the shapes of the three distribution curves.

With regard to the voltages at the other end of the winding, two cases were considered. First, with the phases normally delta-connected, one line terminal was surged with a wave having a 40-microsec. tail while the other two were connected to earth through 350-ohm resistances. The voltage is shown in Fig. 41(*c*) and it is seen that it is negligible. Secondly, the three phases were star-connected and the neutral was left open.* The voltage at the neutral with the application of the same wave at the other end of one phase is shown in Fig. 41(*b*). The maximum voltage here is approximately 56 % of the crest of the terminal voltage and occurs at 70 microsec.

(g) Conclusions.

In the paper a total of 6 different transformer winding arrangements has been examined. It is found that in all cases, despite the widely differing ratings and physical dimensions of the windings, the same degree of wave-flattening decreases the stressing by approximately the same amount.

This lack of any critical dependence of the amount of flattening necessary for a desired reduction of stressing on the characteristics of the particular transformer is of great practical importance. It is the justification of the use of standard degrees of flattening for the protection of sundry transformers whose precise transient characteristics may not be known.

It is also shown how condensers can have no general application for producing the required wave-flattening, since they are only effective in the restricted conditions where a flashover near the apparatus is impossible. Similarly, inductances are shown to be ruled out on account of the amplitude-increase and consequent increased tendency to dangerous flashover to which they give rise.

It is demonstrated how of the wave-flatteners discussed the surge absorber alone has none of these drawbacks, and how the factor of protection determined in its design is maintained under the most rigorous conditions which have been simulated. Operating experience has shown that this degree of protection is adequate.

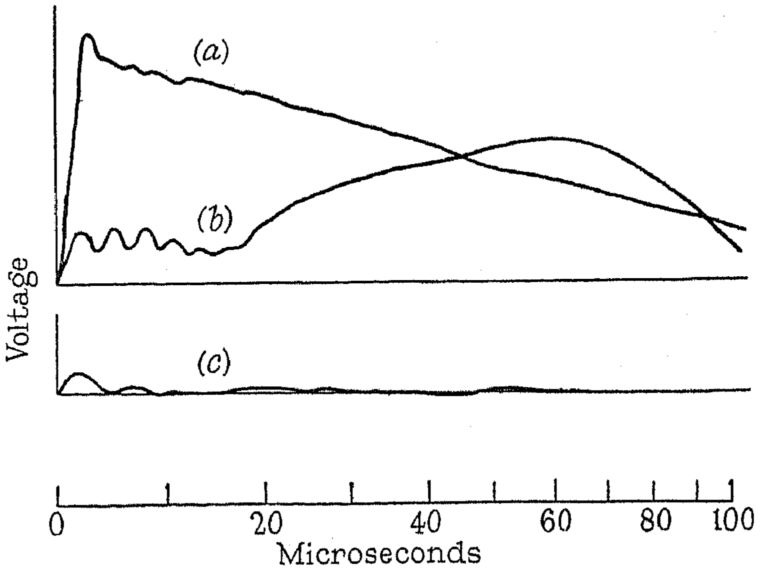

Fig. 41.—Voltage at either end of one phase of a 3-phase transformer connected in star or delta.

(*a*) Applied surge at the line terminal for star- or delta-connection $Z_1 = 350$ ohms.
(*b*) Voltage at other end of winding when star-connected with open neutral.
(*c*) Voltage at other end of winding when delta-connected and earthed through resistance of 350 ohms.

(*a*), (*b*), and (*c*), are all to same voltage scale.

Another fact that emerges is that the reinforcement of a winding for a particular terminal condition does not necessarily increase its strength but may only shift the region of maximum gradient into the non-reinforced part of the winding.

Referring more particularly to direct-stroke phenomena, it is seen that the multitudinous reflections arising do not appear to cause any untoward effects in themselves, and that the severe transformer gradients likely to exist are due both to the greater amplitudes of the surges here compared with those under travelling-wave conditions and to the rapid rate of rise and collapse of voltage. The severity of these gradients cannot accurately be determined until such time as more data are available regarding the rate of rise of lightning voltage and until definite figures relating to impulse ratio with such rates of rise are forthcoming. Nevertheless, sufficient information is given to show that the short durations of the high-amplitude surges caused by direct strokes add complication to the reinforcement problem in transformer windings unless external wave-flatteners are employed.

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* See Bibliography, (36).

(h) Measurement Technique and Oscillograph Circuit Details.

The high-speed oscillograph and the associated equipment used for making the measurements are in matters of major importance similar to those already described elsewhere.*

For all measurements capacitive voltage-dividers have been used, for the reason that their response to very rapid voltage-changes†—such as occur with very steep fronts and flashovers—is not so limited as that of resistance dividers. Further, they are readily shielded and they impose not only a minimum loading on the test object but also a loading which is of the same nature as already exists on a transformer winding.

The loading of such a divider is a minimum when there is no delay cable connected to the low-voltage side, and hence the "controlled" method of surge initiation is employed; that is, the oscillograph circuits are tripped from a tertiary circuit a short time before the impulse generator. Such an arrangement—which has been the authors' standard practice for some years—has the further advantage in that all questions of distortion of the transient in the cable itself are eliminated.

Axial stresses are examined by measuring directly the voltages between coils and across single turns with two capacitance potentiometers.‡ This method is obviously preferable to that where the gradients are delineated indirectly by subtracting graphically the oscillograms of the voltages to earth at each end of a coil. The measurements of voltage across single turns in this latter manner are generally very inaccurate.

Such oscillograms as are shown are arranged in appropriate groups, and in order to facilitate their assembly on the same axes for clarity in comparison they have been traced from the originals.

(6) ACKNOWLEDGMENTS

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(8) APPENDIX

Derivation of the Surge-Absorber Equations

The operational solution for the voltage e_2 in the circuit shown in Fig. 1(*b*) is

$$\frac{2e_1(R_2+pL_2)}{p^3C[L_1L_2-M^2]+p^2[L_1CR_2+L_2C(R_1+Z_1)]+p[L_2+CR_2(R_1+Z_1)]+R_2} \quad . \quad . \quad . \quad . \quad (A)$$

where e_1 is the incident wave, p is $\partial/\partial t$, and $C = C_1 + C_e$. If $S = 1 - K^2$, where $K^2 = M^2/(L_1L_2)$, then equation (1) in the paper can be derived immediately, i.e.

$$\frac{2}{SL_1C}\cdot\frac{p+\dfrac{R_2}{L_2}}{p^3+\left(\dfrac{R_2}{SL_2}+\dfrac{Z_1}{SL_1}\right)p^2+\left(\dfrac{Z_1R_2}{SL_1L_2}+\dfrac{1}{SL_1C}\right)p+\dfrac{R_2}{SL_1L_2C}}\cdot E1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (B)$$

The conditions for non-oscillation of the equation $p^3 + a_1p^2 + b_1p + c_1 = 0$ are

$$a_1^2 - 3b_1 > 0$$

and
$$a_1^2b_1^2 - 4b_1^3 > 27c_1^2 - 18a_1b_1c_1 + 4a_1^3c$$

Applying these and putting $Z_1 = 0$, after manipulation we get

$$\sqrt{\left(\frac{L_1C}{L_2^2}\right)}\cdot R_2 > \sqrt{(3S)}$$

and

$$\left(\frac{L_1C}{L_2^2}\right)^2\cdot R_2^4 - \frac{1+18S-27S^2}{4}\left(\frac{L_1C}{L_2^2}\right)R_2^2 + S < 0$$

as the condition for non-oscillation. The explicit conditions for non-oscillation are therefore as shown in equation (2) of the paper.

In the critical case, $\left[\frac{1}{8}(1+18S-27S^2)\right]^2 = S$

This, when solved, gives $S = \frac{1}{9}$, and $M/\sqrt{(L_1L_2)}$ becomes $\frac{2}{3}\sqrt{2}$.

Under these conditions the operational equation (B) becomes

$$\frac{e_2}{2} = \frac{9}{L_1C}\cdot\frac{p+\dfrac{1}{\sqrt{3}\sqrt{(L_1C)}}}{\left[p+\dfrac{\sqrt{3}}{\sqrt{(L_1C)}}\right]^3}\cdot E1$$

whose solution for $e_1 = E1$ is

$$\frac{e_2}{2} = 1 - \left\{1+\frac{\sqrt{3}}{\sqrt{(L_1C)}}t - \frac{3}{L_1C}t^2\right\}\epsilon^{-\frac{\sqrt{3}}{\sqrt{(L_1C)}}t} \quad . \quad (C)$$

Returning to equation (A), when the coupling is very close so that $L_1L_2 - M^2 \rightarrow 0$, then (A) reduces to

$$e_2 = \frac{2e_1(R_2+pL_2)}{p^2[L_1CR_2+L_2C(R_1+Z_1)]+p[L_2+CR_2(R_1+Z_1)]+R_2}$$

or

$$= \frac{2e_1(R_3+pL_1)}{p^2C[L_1R_3+L_1(R_1+Z_1)]+p[L_1+CR_3(R_1+Z_1)]+R_3}$$

where
$$R_3 = \frac{L_1}{L_2}\cdot R_2$$

When $L_1L_2 \neq M^2$ and when the time-rate of change of the current is great enough to make the inductance of the secondary the controlling factor in the secondary circuit, there is the operational inequality $pL_2 >> R_2$.

Then
$$\frac{p^2M^2}{R_2^2 - p^2L_2^2} = -\frac{M^2}{L_2^2}$$

and
$$e_2 = \frac{2e_1}{pC\left[R_1 + Z_1 + \frac{M^2}{L_2^2}\cdot R_2 + p\left(L_1 - \frac{M^2}{L_2^2}\cdot L_2\right) + \frac{1}{pC}\right]}$$
$$= \frac{2e_1}{pC\left[R_e + Z_1 + pL_e + \frac{1}{pC}\right]}$$

where
$$R_e = R_1 + \frac{M^2}{L_2^2}\cdot R_2 \quad \text{and} \quad L_e = L_1 - \frac{M^2}{L_2^2}\cdot L_2$$

If the time-rate of change of the current is such that the operational inequality $pL_2 >> R_2$ does not hold, then
$$R_e = R_1 + \frac{M^2}{L_2^2}R_2\lambda, \quad \text{and} \quad L_e = L_1 - \frac{M^2}{L_2^2}L_2\lambda$$

and λ, never greater than unity, will depend on the ratio R_2/L_2 and on the shape of the incident wave.

e_2 can now be written
$$\frac{2e_1}{p^2L_eC + pC(R_e + Z_1) + 1} \quad . \quad . \quad \text{(D)}$$

When the incident wave is $e_1 = E(\epsilon^{-at} - \epsilon^{-bt})$, then the solution of (D) gives equations (3) and (4) of the paper.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 13TH APRIL, 1938

Dr. T. E. Allibone: The authors are to be congratulated on their comprehensive analysis of the effect of surge absorbers on different kinds of surges. Many of the curves are based on analyses of hundreds of oscillograms, but I am sorry that the paper does not contain any examples of the oscillograms of voltages appearing across sections or turns of transformer windings, for Dr. Miller has specialized in the difficult technique of recording such oscillograms.

I propose to devote my remarks mainly to wave-flatteners, as these are the only transformer protective devices dealt with comprehensively by the authors. Wave-flatteners are more efficacious in dealing with brief surges of the type which result from direct strokes or from chopped travelling-waves than with long travelling waves. For surges of very short duration the voltages appearing across small sections of the windings can be reduced, as the paper shows, to about one-third of what they would be in the absence of an absorber, but are not the authors really transferring the problems of interturn insulation at the beginning of the transformer from the transformer to the absorber? I would welcome their opinion as to the ability of the absorbers to withstand the very high voltages which will be imposed on the absorber instead of on the transformer. The author's second slide showed that a chopped wave resulting from a direct stroke with a rapid rate of rise of voltage might reach 4 times the magnitude of the highest-voltage travelling-wave (say 700–900 kV) permitted on the 132-kV grid system. Presumably, therefore, the chopped-wave voltage might rise to between 2 000 000 and 3 000 000 volts. Is the 132-kV absorber capable of withstanding such very high voltages? The authors make the point that, unlike the surge arrester, the surge absorber need not be protected by overhead earth wires; are they satisfied that an unprotected surge-absorber can deal with a direct stroke without suffering harm?

The fact that there is so little published information with regard to the exact nature of transformer failures under lightning conditions makes it difficult to assess the relevative importance of the travelling wave and the abrupt direct stroke in damaging transformer windings. I accept the authors' statement that many failures occur between turns and sections, but unfortunately I have not enough experience to be able to say, with them, that "by far the greater number of failures" occur in this manner. A study of transformer oscillations shows that many of the kinds of failure which may occur cannot be avoided by sloping the wave-front; the only way of preventing such failures is to reduce the amplitude of the applied surge. Thus the wave-flattener represents a cure for some types of transformer failures, but not for all.

I should like to draw the attention of the authors to a type of trouble which we were specially made aware of when reading a paper* before The Institution recently. We were told many times that on isolated-neutral systems the neutral terminals flashed-over under surge conditions, sometimes with the accompaniment of transformer failure; this surely proves that long-wave high-amplitude transients arrive at the transformer more frequently than the authors suggest; these surges are not much affected by the presence of an absorber.

It is surely necessary to earth the casing of an absorber as effectively as that of an arrester: because, if this were not done, then under direct-stroke conditions the absorber bushing would flash-over to the casing, the potential of the casing would be raised, and a flashover would occur back to the other bushing of the absorber, so throwing a steep-fronted surge on to the transformer. The best compromise, if the earth connection is not a good one, is to connect the case of the absorber or lightning arrester to the transformer tank.

Whilst I agree with the authors' statement that the provision of condensers in the transformer does not result in the suppression of oscillations, I would mention that by this means oscillations are greatly reduced, and therefore the evil effects of high gradients across the turns and coils are mitigated.

It appears that the authors' absorbers have a fairly large number of turns, and I should like to know what thermal losses are to be expected at 50 cycles per sec. Also, what tests do they consider desirable for such absorbers?

In Fig. 2 the wave-fronts of surges after passing through the absorber are given as just over 1 microsecond, even though the ratio L_1/C_1 varies by about 9 or 10 to 1; yet in Fig. 6 these wave-fronts are quoted as about 2·5 microseconds. Is there any specific value of wave-front at which the authors have aimed in designing the surge absorber, and what is the reason for this large variation in the wave-front?

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* *Journal I.E.E.*, 1937, vol. 80, p. 117.

In their "Conclusions" (page 214) the authors state that operating experience has shown that the degree of protection afforded by these absorbers is adequate. Perhaps they will indicate the range and nature of the operating experience which they have had with the type of absorber described in the paper.

Finally, I should like to know why they chose condensers as a standard of comparison for their absorbers, seeing that condensers are not widely used as protective devices on any transmission line.

Mr. E. T. Norris: The paper gives the results of many years' study by the authors and their associates of the surge characteristics of transformers and protective devices. Progress in the technique of the protection and measurement of surges is so rapid that it is difficult to say at any time what are the latest developments. The paper, however, appears to break new ground in two directions in particular: (*a*) in the accurate study of interturn and intercoil stresses within transformer windings; and (*b*) in the reproduction of direct-hit conditions.

The keynote of the paper is the authors' emphasis upon the relative importance of axial stresses in the windings in comparison with the radial stresses in the major insulation. This is justified by the fact that operating experience, technical analysis, and full-scale tests combine to show that wave-front or wave-tail steepness and not amplitude is the surge characteristic fatal to transformer windings.* A broad summary of the position reflecting world experiences over the last 40 years is given by a historical survey. In the early days of electrical engineering, both major and intercoil insulation were based upon a factor of safety of 3–4 over working conditions, and test voltages in this ratio were standardized. Early experience compelled a large increase in the intercoil insulation, and values at present in use are 100 to 1 000 times greater than would be required by normal 50-cycle stresses. On the other hand, no increase has been found necessary in the major insulation, and standard test voltages are still based on the factor of safety of 3–4 established by general engineering practice. The authors' reference to Bibliography (25) shows that, even so, intercoil and interturn insulation is still the weakest under lightning-surge conditions. The original patent on the surge absorber referred to in the latter part of the paper was taken out by Mr. L. C. Grant in 1923. Experimental work in its development has been carried out continuously since that time. For many years, of course, these experiments were of a qualitative nature as the high-speed cathode-ray oscillograph was not available and the technique of surge measurement was relatively crude. In recent years, however, quantitative measurements, such as those described in the paper, have permitted practical design of surge absorbers having a consistent and standard degree of effectiveness.

A large proportion of the investigation described in the paper is in the nature of pioneer experimental work, for which there was no precedent or independent measurements to form a criterion of accuracy and reliability. It is therefore an important confirmation of the authors' work that the more important measurements have been made on a standard surge-absorber by the National Physical Laboratory with practically identical results. This work is referred to in the 1937 Report of the National Physical Laboratory, page 54.

Mr. H. S. Holbrook: The authors' solution to the problem of improving the surge protection of power transformers is to add outside the transformer a piece of apparatus which they call a wave-flattener, although it really only lengthens the wave-front. I am of opinion, however, that they show that an amplitude-flattener is more important. The authors point out that for a given wave-form the stresses in the transformer will vary with the amplitude of the terminal voltage, so that if we can reduce that amplitude we achieve the desired object. They also emphasize again and again that perhaps the most dangerous occurrence near a transformer is a flashover, especially a bushing flashover. The apparatus which they are putting forward, however, according to Fig. 2, actually increases the voltage which is going to be applied to the transformer, and it does that while at the same time lengthening the wave-front. It is well known that if the front of a wave is lengthened the flashover value of a given bushing will be reduced; probably for a change of front such as the authors mention, of 0·2 to 3 or 5 microsec., the voltage required to flash-over the bushing will be very nearly halved. There is then a distinct risk that the installation of such an apparatus as this may cause a dangerous occurrence, namely a flashover on the bushing of the transformer which it has been put in to protect. I should be interested to know what precautions the authors take against such an occurrence.

Considerable reductions in the axial stresses between coils are obtained by the simple shields referred to in Section (3)(*b*) of the paper. These have the great advantage over any external apparatus in that they are part of the transformer and there is no fear of the protective device being found disconnected when the time arrives for it to be used.

Dr. P. F. Stritzl: I am disappointed to find that the authors have confined their research to one side of the surge problem, namely that of wave-front steepness, since it is now almost generally agreed that the maximum peak of the surge is equally important, if not more so.

I should like to suggest the addition to the authors' Bibliography of two important papers, one by Dr. Bewley* and the other by Dr. Willheim.† In these papers much greater emphasis is laid upon the importance of the time factor than in the present paper, and the conclusion is reached that a great number, if not the majority, of breakdowns do not occur on the wave-front but on the tail of the wave. This conclusion has been confirmed by a great number of experiments. Furthermore, the oscillation that takes place between the terminals and the neutral point causes the point of maximum stress to travel along the winding, and the mere reinforcement of the end turns, or the addition of an external wave-flattener, will not make the transformer surge-proof. This can be achieved, i.e. the oscillation can be prevented, by a suitable distribution of the capacitances between turns and to earth.

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* E. T. Norris: "Protecting Transformers from Surges," *Electrical Review*, 1937, vol. 120, p. 910.

* *Electrician*, 1934, vol. 113, p. 297.

† *Elektrotechnik und Maschinenbau*, 1932, vol. 50, pp. 16, 28.

Even if the surge absorber is regarded as a satisfactory means of safeguard against those very steep surges that may cause a breakdown before the peak voltage is reached, the authors will certainly agree that the absorber cannot possibly deal with the tail of a surge or with internal oscillation, or neutral-point reflection, nor can it afford protection to apparatus other than transformer windings.

The alternative to the surge absorber is the arrester (or diverter) briefly mentioned on page 189. As the authors have pointed out, this device is primarily intended to reduce the surge-voltage amplitude to a value below the surge flashover-voltage of insulation. This is achieved by discharging the surge energy to earth with a time-lag shorter than that of the insulation and at a very high rate of current. The result is illustrated in Fig. A, which refers to a typical 30-kV installation. While protecting all types of insulation which a "flattener" would leave unprotected, this reduction of the peak value would not in itself afford any protection to the insulation between turns, with which the paper is chiefly concerned. Fig. A shows, however, that the arrester, instead of flattening the surge front, reduces its duration very satisfactorily. This, in my opinion, is an even more effective means of protecting the interturn insulation, since the occurrence of an axial breakdown is a function of both steepness and time.

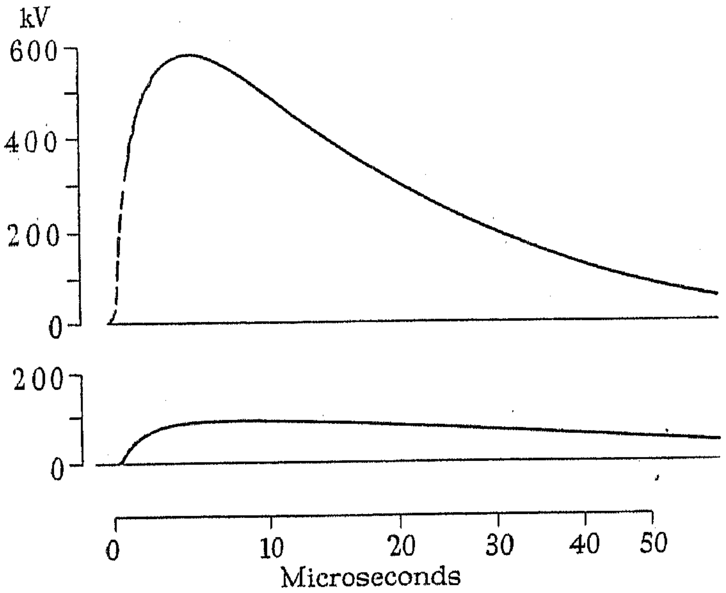

Fig. A.—Impulse wave in 30-kV terminal station.

Upper curve: without protection.
Lower curve: with 30-kV S.A.W. arrester.

Thus the arrester reduces all kinds of stress, and it seems not surprising that this principle of protection has been adopted by all the principal manufacturers, particularly since the discovery of voltage-dependent resistances made it possible to combine the discharge at a very high current rate with a definite interruption of the discharge at the end of the half-cycle.

A practical example may be of interest. In a certain network, arresters were installed in all 56 substations, and the result for a period of 12 months was as follows: Without arresters, 3 transformers damaged, 47 fuses blown; with arresters, no transformers damaged, 8 fuses blown.

The authors mention that there are "considerable limitations" to the installation of surge arresters. The firm with which I am connected has installed over 80 000 high-voltage surge arresters in various parts of the world, including about 1 000 in this country, and we have found that it is perfectly sufficient to connect the arresters to the station earth. Where the earthing resistance is high, the station earth and with it the whole station assumes a certain potential, but this does not impair the protective effect. Difficulties may be encountered sometimes in the case of small pole-mounted transformers, but as a rule these small transformers are left unprotected for reasons of economy.

What evidence have the authors to prove their claim that in actual practice surge absorbers give protection against direct strokes? It is difficult to see why an absorber should be more capable of dealing with this type of trouble than an arrester. I know of not a single case where a transformer protected by a surge arrester of the S.A.W. or an equivalent type, was damaged even by direct strokes. In several cases when direct strokes have occurred the surge arresters themselves were destroyed, in place of the transformers which they saved. In spite of this satisfactory experience it is not claimed that surge arresters give reliable protection against direct strokes, and I would expect an absorber with its inductance to be in a no more favourable position.

Dr. Allibone has already referred to the danger caused to the surge absorber itself by transferring the stress between turns from the transformer to the protective device. It seems to me that any type of "flattener" if used at all, should be shunted by a surge arrester, or at least by a voltage-dependent resistance, to protect it against the high stress caused by the passage of a transient.

I agree with the authors' remark about Petersen coils in Section (2)(*b*), but I would mention that the Petersen coil may give some indirect protection to transformers, inasmuch as it limits the earth current and thereby the amount of damage done to the transformer should it break down under the influence of a surge.

Mr. E. Kilburn Scott: We have no trouble in obtaining good earths for transmission lines in this country, but it must be difficult in parts of the world where periods of drought may be six or more years, e.g. between the Nile valley and Siwah. Presumably in such places it would be necessary to connect the pylons together and run an earth wire to an oasis where there is some damp earth. How are the natives prevented from stealing the copper wire? They are prevented from taking telephone wires in South India by charging them at high voltage during the dark hours.

Some years before the War whilst I was working on an electric furnace, there was trouble owing to the arc going in and out and causing surges. Although the step-up transformers were immersed in oil and the end insulators extra-insulated, breakdowns still occurred. The trouble was stopped by connecting in the circuit three coils wound on tubes of papier mâché, such as those in which drawings are posted.

Mr. J. E. L. Robinson: It is a fact of experience that transformers when broken down by lightning or by impulse test usually fail in consequence of axial stresses, and this relative weakness of the axial insulation compared with the major insulation is a point of considerable importance to advocates of the wave-modifier method of protection. When lightning failures occur the damage is frequently so extensive that traces of the origin of the failure are obliterated, and when it is possible to discover the mode of failure this can normally only be done on completely dismantling the transformer. Difficulties such as these probably account for the scant information on failures obtained from operating authorities. It is clear that the greatest fund of information should be in the hands of the manufacturers who have to repair the damaged transformers, and it is a pity that more of this information has not been made available. In this connection the conclusions of the prominent authorities cited in the paper are, however, important.

Apart from operating experience, abundant secondary evidence is of course available from results of laboratory tests to breakdown and from technical analysis. This is very fully dealt with in the paper, but it can be shown that this weakness of axial insulation relative to major insulation under impulse conditions is foreshadowed in the various standard specifications on which the insulation design of transformers may be based and in the order of severity of 50-cycle tests which a transformer may be constructed to meet.

Taking the case of a typical 110-kV system, the argument is as follows: The minimum basis for the design of major insulation is B.S.S. No. 171—1936, and this requires a 1-minute test of twice the line operating voltage. It is obviously impossible to generalize on the factors of safety employed by different manufacturers above this test, but from the consideration alone of the test causing no damage it would certainly seem that the factor of safety cannot well be less than 2·0. Moreover, the impulse ratio of the major insulation above the 1-minute crest 50-cycle breakdown value may vary somewhat, but 2·0 is again a conservative value for 1/50 or 0·2/40 impulse conditions. For a line operating voltage E it therefore follows that the 1/50 impulse strength of the major insulation will be at least $2\sqrt{2}E \times 2 \times 2$, or $11{\cdot}3E$.

For a 110-kV system the ratio of minimum 1/50 impulse flashover to peak phase operating voltage is some 5·2. The maximum possible 1/50 impulse amplitude is therefore $5{\cdot}2 \times \sqrt{2} \times E/\sqrt{3}$, or $4{\cdot}25E$. Again, for the longest-backed practical impulse there is ample evidence that the maximum voltage to earth on the major insulation throughout the winding will not be greater than some 1·25 times the amplitude of the incident impulse. Accordingly the maximum voltage which can arise on the major insulation under 1/50 impulse conditions is $4{\cdot}25E \times 1{\cdot}25$, or $5{\cdot}3E$.

From these figures it follows that the major-insulation safety factor under 1/50 impulse conditions must be at the very least $11{\cdot}3E/(5{\cdot}3E)$, or 2·1. This represents a considerable measure of safety, and it would therefore seem that there should be no question of a transformer which withstands the standard test failing under these conditions.

The argument can be similarly extended to show that there is still a margin of safety under very severe flashover conditions.* In any case I have shown in the discussion before the North-Western Centre on this paper† that the important amplitude co-ordinating property of the surge absorber limits the amplitude of the major-insulation voltage under the severest conditions to about the 1/50 impulse minimum flashover value. Accordingly when the surge absorber is employed the safety factor of at least some 2·1 obtains for the major insulation for impulse conditions of any severity.

Turning to the question of the axial or interturn insulation strength, it is here more difficult to make a general estimate since additional and more complicated factors must be considered. One of these is the value of the constant α for the transformer and its effect, together with the further geometry of the winding, on the concentration of stress across interturn insulation. The order of these factors is now well established, and for a transformer with 80 winding sections and α equal to 10, under 1/50 impulse conditions the portion of the terminal voltage appearing across normal between-turns insulation would be some $\frac{2 \times 10}{80} \times 100$ or 25 %. It has already been shown that the maximum 1/50 impulse amplitude (minimum 1/50 flashover value) is $4{\cdot}25E$. The corresponding voltage on the interturn insulation will therefore be some $0{\cdot}25 \times 4{\cdot}25E$, or $1{\cdot}1E$.

In the design of interturn insulation a minimum requirement is that set forth in B.S.S. No. 422—1931. This requires a type test on the normal interturn insulation equivalent to $0{\cdot}133E$ for 1 minute. Since this is a type test only, a lower safety-factor than for the major-insulation test might conceivably be used, but even if a factor of 2·0 is again assumed, and also an impulse ratio of 2·0, the impulse strength of this insulation will be some $0{\cdot}133\sqrt{2}E \times 2 \times 2$, or $0{\cdot}75E$.

Thus it appears that the axial strength of a transformer designed in accordance with B.S.S. No. 422 would be of the order of $0{\cdot}75E/(1{\cdot}1E)$, or 70 % of the maximum amplitude of 1/50 impulse which it could experience. For severe flashover conditions the severity is of course considerably greater. Thus for a 0·5-microsecond flashover the impulse ratio is some three times greater, and in addition the severity may be increased by a further factor due to the oscillation on flashover. It follows, therefore, that the axial strength will only be of the order of at most 70/3 or 23 % of the voltage to which it would be subjected under this condition. Even when the interturn insulation of the normal transformer has been designed to comply with a more rigorous specification there will be still a considerable margin between its strength and the severity of the over-voltage to which it may be subjected.

It will be clear that the foregoing analysis can be more readily made for specific cases where all the factors can be individually assessed. The values assumed here are, however, all typical and clearly illustrate the order of the discrepancy between major and axial insulation to which design in accordance with the standard 50-cycle insulation tests leads. It is just this discrepancy which is the underlying reason for the operating experience that transformer lightning failures are usually due to axial stresses. It is also this discrepancy which it is the first purpose of the surge absorber to remove, and figures such as those deduced here are analytically the basis of the 1/50 impulse surge-absorber performance figure of the order of 3, which, as stated in the paper, has been found as a result of operating experience to give satisfactory protection.

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* Thus under 0·5-microsecond flashover conditions the line-insulator impulse ratio will be some 3·0 times the 1/50 impulse value, and the 1·25 increase throughout the winding factor will not arise. The impulse amplitude will therefore be 3·0/1·25 or 2·4 times the 1/50 impulse value. Again, the major-insulation impulse ratio will here be greater than the 1/50 impulse value, so that a safety factor will still exist.

† See page 225.

Mr. J. F. Shipley: I should be interested to know how many transformers break down every year owing to lightning troubles. One might infer from the paper that the transformer is extremely vulnerable, whereas the contrary is the case. I have knowledge of several high-voltage systems operating in very difficult districts from the point of view of lightning, but cannot remember any cases of transformers breaking down. There have, however, been one or two instances of alternators breaking down and the surge passing through transformers which one would have thought would have acted as a protection. One transformer manufacturing firm has boasted that, if the purchaser of its transformers would only do away with all lightning protection gear, it would guarantee the safety of the whole system from lightning.

Mr. A. A. Bolsterli (Switzerland) (*communicated*): In the face of the authors' rather summary condemnation of condensers as a means of surge protection of transformers, it is interesting to note that after a great deal of thorough investigation several large electricity undertakings in Finland and Sweden have in the last few years installed condensers for surge protection on lines of voltages up to 120 kV. I should like to point out that the capacitances used by the authors in their tests are considerably smaller than those which are to-day quite generally considered necessary for surge protection. Only Figs. 27 and 36 refer to condensers whose capacitance is within the range of values used in good practice. For these the results presented by the authors show clearly that the condenser is a remarkably efficient tamer of surges, when of adequate capacitance.

The authors do not deny that any amount of flattening can be obtained by means of condensers, but they advance against them the objection that they afford no protection when a flashover occurs at or near the condenser. They show, in Figs. 20, 21, and 28, examples of the ensuing oscillation in the local circuit. Both Fig. 20 and Fig. 21 are for capacitances considerably below the "protective" range. Only Fig. 28(*b*) approaches the size that might be considered for an e.h.t. line; here the frequency of oscillation, and hence the time-rate of voltage-change, is greatly reduced. By diverting the flashover to a nearby co-ordinating gap, instead of allowing it to occur at the condenser, it is possible, within limits, to increase for a given condenser the inductance of the local circuit and hence to reduce its frequency in accordance with the relation

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

Since the time-rate of change of voltage is proportional to the frequency, it is easily seen how the former can be reduced by increasing L and/or C.

Much more important, however, is the fact that the transient in the local circuit need not be oscillatory at all, but can be rendered aperiodic, with consequent vast reduction in the time-rate of voltage collapse, by introducing damping resistance. The most practical way in which this can be done consists in providing separate but nevertheless thorough earths for both condenser and co-ordinating gap, the earth resistance between the two earths assuming the role of a damping resistance. Recent tests (as yet unpublished) made at the Olten-Gösgen open-air surge-testing laboratory of the Commission for High Voltage Research of the Swiss Association of Electrical Engineers, under the direction of Dr. Berger, have clearly demonstrated the efficacy of this measure. Co-ordinating gaps were tried at various distances up to 1 000 m. from the condenser, with earths interconnected by a metallic conductor and with separate earths. In a typical test the co-ordinating rod-gap was 50 m. away from the $0 \cdot 1$-μF condenser. With the earths of condenser and gap solidly interconnected by a copper conductor of low ohmic resistance, the voltage at the condenser, upon flashover of the gap (set for 50 kV), was oscillatory and the maximum rate of change of voltage was 18 kV per microsec. With separate earths, the decay was aperiodic and the maximum rate of change only 1 kV per microsec. In both cases the incoming surge was a 1/50 wave with 101-kV crest. The condenser flattened the front of the wave from 101 to $2 \cdot 4$ kV per microsec., which amounts to a reduction of steepness to 1/40th of the original value. The tests at Olten-Gösgen have shown generally that the effect of the condenser corresponds closely to predictions made on the basis of calculations.

Looking at surge protection from the wider angle of co-ordination of insulation, I find that the authors have not stressed a result of wave-front flattening that is of considerable practical importance. On page 189 they refer to the limitations of the rod co-ordinating gap which are due to the large impulse ratio it exhibits for steep-fronted waves. For these the gap withstands a higher voltage without flashing-over than is good for the insulation of transformers, whilst for less steep fronts the time/breakdown-voltage curves of gap and insulation are compatible. By flattening incoming waves, be it by means of condensers or by surge absorbers, the rod-gap can therefore be rendered the dependable safety-valve that is required if the schemes of co-ordination of insulation are to work reliably.

To do justice to condensers, it should be emphasized that their usefulness as a protective device is not confined to their wave-flattening effect. With capacitances ranging from $0 \cdot 044$ μF at 120 kV to $0 \cdot 25$ μF at 20 kV, an appreciable reduction in the wave amplitude is obtained. The majority of waves arriving at the station will be reduced by the condenser below the flashover amplitude of the co-ordinating gaps in the station, with consequent improvement in continuity of service and reduced maintenance of switchgear. One of the great advantages of the condenser is that its effect can be accurately predicted by calculation. If the shape of the incoming wave is known, not only the flattening effect but also the reduction of amplitude is well defined. The curves in Fig. B* enable one to read off, for certain wave-shapes and any given capacitance of condenser, the percentage reduction in amplitude when the condenser is located at the open end of a line. The curves are based on triangular waves, but are not affected greatly if the wave-shape is different but not the charge. Since the crest of the modified wave depends largely upon the charge, in coulombs, of the wave, the length of wave-tail, or the time to half value, has a large influence upon the amplitude, as is seen from the curves. In this connection it is worthy of note that, according to statistics on lightning, waves of very large amplitude are as a rule short, and vice versa, the charge only rarely exceeding 0·03 coulomb. This justifies the conclusion that, for the majority of waves, the condenser will modify the wave-crest to values at or below a fairly consistent and predictable average level. As an example, we read from the curves in Fig. B that with an incoming surge of triangular shape with a 3-microsec. front and a half-time of 50 microsec., a 0·2-μF condenser at the end of the line will reduce the over-voltage there to 30 % of that which would occur without the condenser. If the front were 1 microsec. only, but the total length (or charge) of the surge the same, the result would not be materially different.

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* From an article by M. Wolff in *Kraft och Ljus* (Helsingfors), 1938.

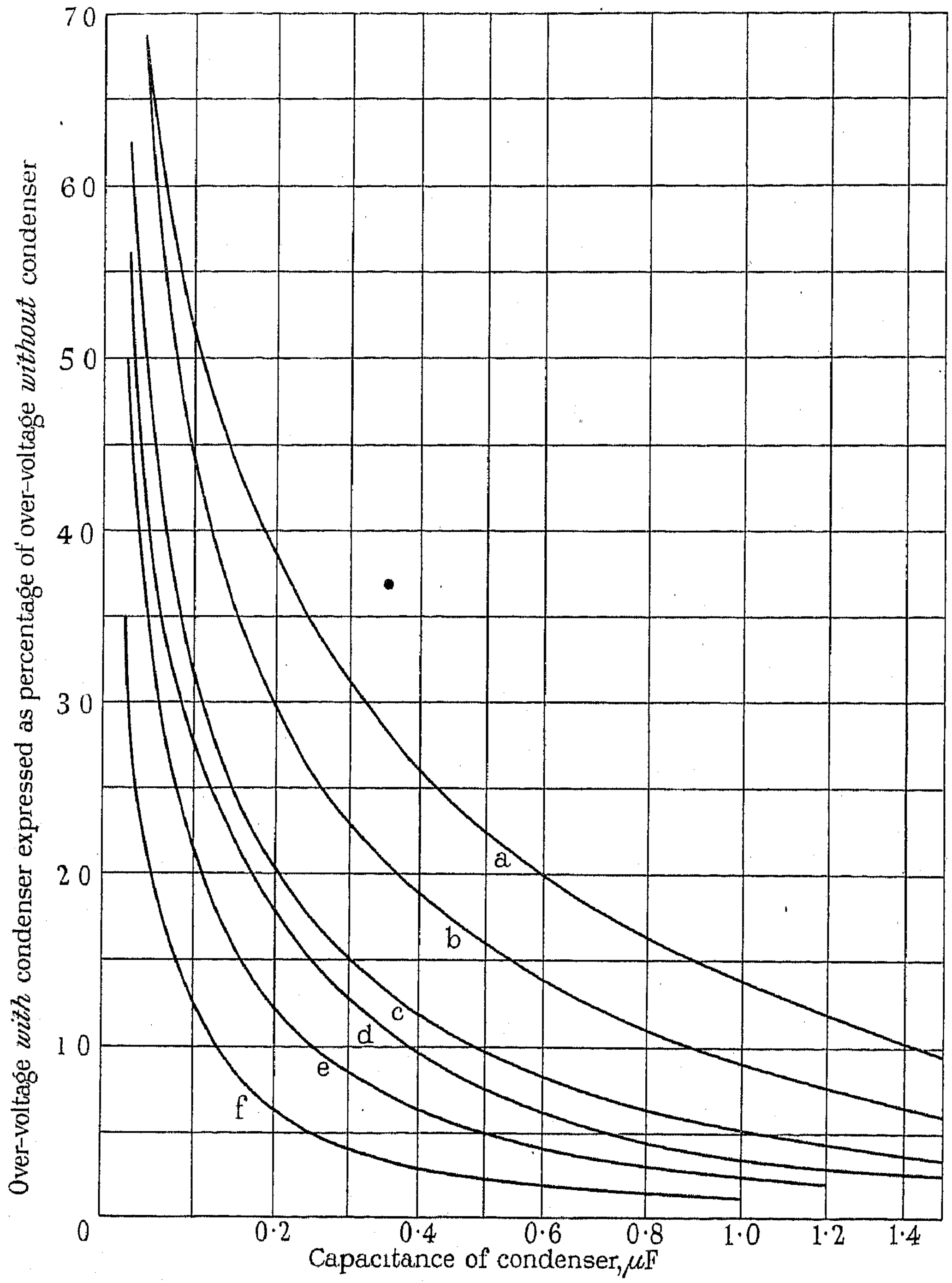

Fig. B.—Ratio of over-voltages at end of line, due to impinging triangular waves. Condenser connected at open end of line.

Curve *a* : 0/75 triangular wave.
„ *b* : 3/50 „ „
„ *c* : 3/25 „ „
Curve *d* : 3/20 triangular wave.
„ *e* : 3/12·5 „ „
„ *f* : 3/5 „ „

As the physical size of a condenser of given capacitance increases roughly as the square of the voltage, the cost may be thought excessive for the higher voltages. This is, however, not the case, inasmuch as by means of tappings the condenser can be made to perform also the functions of the potential transformer which would otherwise have to be installed. Whilst actual operating experience will, in the last analysis, decide the place of the condenser as a surge-protection device, it possesses inherently the requisite properties and can compete also from a cost point of view.

Mr. J. W. Gibson (*communicated*): On page 190 the authors state that with terminal voltage surges persisting for times less than 20 microsec., the amplitude of the voltage across the major insulation is probably everywhere less than at the terminal. It would be of considerable interest, therefore, if the authors would show a typical distribution curve of the voltages to earth for the case of a terminal voltage persisting for only a few microseconds. This seems an important point, since in the paper it is pointed out that the terminal voltages under direct-stroke conditions may rise to something of the order of 5 times the normal surge flashover voltage.

Regarding the voltage gradients along windings, a large number of the authors' gradient-distribution curves show that the windings of the transformers tested were, for travelling-wave or flashover conditions, most highly stressed in a fairly large region below the line-end reinforcement. It is also interesting to note that the gradients near and at the neutral are very considerably less than those at the line end. I would therefore ask the authors whether they have had any practical experience confirming their experimental findings.

Mr. J. Savage (*communicated*): I am connected with the Hastings Corporation undertaking, having a rural electricity distribution area of 155 square miles in East Sussex, with 76 miles of overhead lines operating at 11 kV, 107 miles of overhead lines at 400/230 volts, and 22 miles of e.h.t. and 32 miles of l.t. underground cables. This area is subject to a greater number of thunderstorms than surrounding districts, and prior to the installing of surge protective devices complete interruption of the electricity supply to the rural area on account of such storms occurred on an average 11 times each year. The damage done included flashing-over at 11-kV terminals and punctured windings of a 100-kVA 3-phase transformer, which had to be returned to the makers for reconstruction; failure of 90 yards of underground cable, which was punctured at hundreds of points; and complete burn-out of several sets of current transformers and two 11-kV oil switches. Surge absorbers were installed in October, 1933, at terminal positions of overhead lines on one section of the 11-kV system, and during the next 12 months there were no failures on that section whereas 12 failures occurred during thunderstorms on the remainder of the system. The whole system is now equipped with surge absorbers, together with auto-valve surge diffusers in positions on existing lines where it was inconvenient to fit the former type, and as the result protection against surges during thunderstorms is practically complete. On this system protection is given to the switchgear and transformers, including down-leads.

In Fig. 30 the authors indicate the magnitude of the terminal voltage on the transformer side of a surge absorber; I should be pleased if they would indicate its magnitude on the line side at the same instant, and state whether any building-up of potential or reflected waves is produced at this point. Further, I note that in several diagrams showing positions for surge absorbers no earth connection is indicated, whereas in practice a good earth is considered essential; will the authors please indicate the altered protection provided in the event of the earth resistance having values from 0·5 ohm to 20 ohms?

[The authors' reply to this discussion will be found on page 228.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 12TH APRIL, 1938

Prof. E. W. Marchant: It does not seem very long since Dr. Miller and I were engaged in the investigation of the effective inductance and resistance of coils with metal plates adjacent to them, an arrangement which is not very dissimilar from the surge absorber dealt with in the present paper. I do not imagine that the number of flashovers from direct lightning strokes in this part of England is very considerable, but in South Africa and in many other places where large transformers are installed flashovers due to lightning are a very serious problem. I remember that in South Africa 8–9 years ago this was one of the most important considerations which had to be dealt with in connection with the maintenance of an efficient supply for the Colenso–Pietermaritzburg Railway.

One reason why I am particularly interested in this paper is the development it indicates in the methods of examining phenomena of very short duration. I am reminded of the time, a good many years ago, when Mr. Duddell and I were engaged on the development of the very earliest oscillograph; we thought we were doing rather well when we were able to record a phenomenon which lasted about a hundredth part of a second. The scale has since gone up 10 000-fold, because the time scale of the oscillograph of which we have seen records has been graduated in microseconds. A great deal of light has been thrown on what is happening under conditions which it was impossible to record before the cathode-ray oscillograph was developed.

One of the points of the greatest interest in the paper is that inductance, which used to be regarded as a standard method for the protection of apparatus against the effect of lightning surges, is really harmful in certain cases. Thus the second experiment which Dr. Miller showed, where the flashover occurred on the other side of the line from the tower, indicates that for dealing with a direct stroke under these conditions inductance is worse than useless.

Another thing that inductance does under these conditions is to tend to produce very high-frequency oscillations in the circuit. We have been making investigations in Liverpool for a good many years on the effect of very high-frequency stresses on the behaviour of dielectrics, and it is found that there is a very remarkable change in the electric strength of all insulating materials at high frequencies. If a material like porcelain is tested at a frequency of the order of 1 million cycles per sec. the electric strength is found to be only 10 % of that at ordinary power frequency. With sphere-gaps in air there is a very considerable reduction in breakdown voltage at high frequencies, and much more between needle points. If inductances are used, therefore, and these high-frequency oscillations occur, there is more likely to be a breakdown of the dielectric than if the inductance were not present.

I am particularly interested in the authors' remarks about the distribution of stress along the coils of a transformer. This is not very different from the distribution of electric stress along a string of suspension insulators, where the capacitance due to the junction piece between two insulators leads to an uneven distribution of electric stress along the string.

Mr. E. T. Norris: The paper deals essentially with the various external means available for the surge protection of power transformers. The work on which the paper is based involved a study of the internal stresses in transformer windings, and as a result much interesting information is given on the behaviour of these windings under surge conditions. All of the transformers employed were of normal construction, in accordance with the existing British Standard Specifications, and were typical of modern practice. It is obvious from an examination of Figs. 9, 38, and 39, among others, that methods of reinforcement which have hitherto been common practice are not very effective, and in some cases are even harmful. Most of the authors' measurements show that the surge strength at the line end has been increased at the expense of the surge strength farther down the winding. Results such as these have suggested that reinforcement is bad and that uniform turn insulation should be adopted. It must be remembered, however, that the reinforcement hitherto specified has been determined mainly by qualitative argument supported by operating experience. The latter was not of much help, as in most cases the cause is obscured by the effect. Accurate quantitative experimental work such as that described in the paper has now made it possible to study in detail the internal stress distribution and to design insulation reinforcement giving consistent and uniform improvement in the surge electric-strength throughout the windings. In some cases it is possible to design a transformer with sufficient surge strength by this means alone, and it then becomes a matter of economics whether external protective devices such as a surge absorber are preferable.

The only alternative method of reducing the inter-turn and inter-coil stresses within the windings is the non-resonating or shielded construction referred to by the authors. A completely shielded transformer would give an initial voltage distribution identical with the final distribution, but this ideal is far from obtainable in practice. In most cases the shields are localized to give partial protection, the degree of which varies among different manufacturers and ranges from the simple electrostatic end ring to a complicated series of capacitances between the line terminal and different parts of the winding. The use of such artificial means to make the initial surge-voltage distribution similar to the power-frequency distribution implies that the two are fundamentally dissimilar. This is not the case, however, and the difference is due to the fact that in power transformers other factors, such as mechanical and thermal requirements, have to be taken into account and in some cases given precedence over electrical insulation considerations. If transformers could be designed with uniform power-frequency dielectric field, surge distribution would be satisfactory. A 500 000-volt testing transformer designed 16 years ago illustrates this point: at that time it was the highest-voltage transformer designed and built in this country, and as the voltage-increase was considerable I subordinated economically thermal and mechanical considerations to insulation requirements and designed the transformer to have a virtually uniform 50-cycle dielectric field. That transformer, which has given no trouble and is still in satisfactory operation, is almost completely non-resonating under surge conditions, in accordance with the most modern principles.

Mr. J. B. Hansell: The authors have established that the surge absorber reduces the voltages between turns and coils of a transformer, but except in the case of a very short impulse wave it does not seem to reduce the amplitude of the wave, and it therefore offers a rather limited protection to the major insulation.

It is a comparatively easy matter to provide adequate major insulation for a simple winding, but it is more difficult to insulate mechanical parts, such as " on load " or " off load " tapping switches, as the best mechanical design is not necessarily the best from an insulation point of view.

Tapping switches are for various reasons usually connected to the middle of a transformer winding, and in the case of a delta-connected winding or of a star-connected winding with insulated neutral, if long impulse waves of like polarity arrive simultaneously on two phases of the transformer, as is a fairly common occurrence, the voltage appearing on the tapping switch will be considerably higher than the voltage at the line terminals. This point was illustrated in a recent paper by Messrs. Allibone, McKenzie, and Perry.*

It seems, therefore, that if an external device is used for protecting a transformer, a device which reduces the amplitude of an incoming wave will offer better protection than a wave-flattening device, because it not only reduces the voltage between turns and coils but it also protects the major insulation of the transformer and its auxiliaries. Further, it protects switchgear and kindred apparatus in its neighbourhood.

On page 188 the authors refer rather briefly to the lightning arrester, which is a device of this nature, and point out that it must be shielded from direct strokes and connected to a low-resistance earth. Is not a low-resistance earth also a necessity for the surge absorber? A stroke to the line near the absorber will cause the line terminal to flash to the absorber case, and, unless a low-resistance earth is used for the case, the lightning current of 40 000 amperes passing through the resistance may raise the case to a voltage above earth sufficiently high to cause the other terminal to flash-over, and the absorber will then be short-circuited and rendered useless. In view of this, and of the particular stress laid by the authors on the difficulty of obtaining low values of earth resistance, I should like to ask whether an absorber designed for a low-voltage line is effective in protecting against a stroke to the line near the absorber.

In considering the relative advantages of protective apparatus, it is necessary to take into account the effect of each on the continuity of supply. The lightning arrester functions by offering a low-impedance path to earth for surge currents and a high-impedance path for power currents; for this reason, although the charge on the line due to impulse voltage is drained to earth, it is not followed by power current and consequent interruption of the supply. When used for protecting apparatus in a terminal station, it reduces the impulse voltage in its neighbourhood and thereby prevents flashover. When a protective device is not used, or when the protective device is a series apparatus such as a surge absorber, the amplitude of an incoming impulse wave is increased considerably by reflection at the terminals of the transformer or surge absorber, and the possibilities of flashover and interruption of the supply are clearly greater than when a lightning arrester is used for protection. From the point of view of continuity of service, the advantage seems to lie with the arrester type of protective device.

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* *Journal I.E.E.*, 1937, vol. 80, p. 117.

Fig. 30(*a*) shows a record of the voltage on a transformer terminal, produced by a direct stroke to the terminal, the circuit conditions being as shown in Fig. 29. The first positive loop indicates the rise in voltage due to the stroke, followed by a collapse due to the flashover of the terminal. After an interval of less than 2 microseconds a reflection from near the first tower causes the voltage on the terminal to reverse. Goodlet has estimated the wave-front of a lightning stroke as being $1\frac{1}{2}$–2 microseconds, and presumably the tail will be much longer. In view of this, would a reversal such as is shown in Fig. 30(*a*) be possible in the case of an actual stroke?

Dr. T. E. Allibone: The authors have shown that the surge absorber may prevent breakdowns between turns of transformers, especially transformers of the kind used in their investigations. The facts about transformer failures in service are unfortunately very hard to obtain, and it is not easy to prove that absorbers have saved transformers from damage in service. Mr. Norris once said that customers were so satisfied with surge absorbers that very many of them had placed repeat orders, and it was therefore argued that the surge absorbers must have proved of great value to the purchasers; the reply given to Mr. Norris on that occasion was that exactly the same thing could have been said of inductance coils, and yet, as the authors have shown in this investigation, the inductance coil has extremely harmful effects. So any argument based on the fickle index of public opinion is no argument to those genuinely interested in the truth.

The paper shows in a very thorough manner that when a coil of some millihenrys' inductance and some millimicrofarads' capacitance, suitably damped with a certain amount of resistance, is placed in front of a transformer winding, the rate of rise or collapse of voltage at the transformer terminal will be slow compared with that at the absorber terminal. A criticism of the absorber in the past has been that it does not do what is now claimed for it, and I think an explanation of the difference in performance would be welcomed. My own criticisms* were based on tests on a 33-kV absorber which were at variance with the authors' results.

The case for the use of the absorber as described in the paper is based on the hypothesis that the most frequent causes of failure of windings are direct strokes and high axial stresses in windings created by rapid rates of change of voltage. Even if this were true—and it is exceedingly difficult to prove or deny—the other causes of failure of transformers would not be affected by the provision of wave-flatteners. Wave-flatteners would be of no assistance, for example, to transformers the major insulation of which was not as high as the axial insulation, and they would not reduce the voltage to earth at tapping-switches or across solid insulation between disconnected coils at tapping points or between physically adjacent coils of a re-entrant-type winding where the coils are spaced electrically by some considerable fraction of winding. Nor would they reduce the number of neutral-point flashovers now experienced with isolated-neutral systems or with earthed-neutral systems on such of the transformers as have their neutrals insulated. I doubt whether they would affect the voltage appearing on the l.t. side of the transformers, and therefore switchgear and alternators would not benefit. Finally, there are still many cases where backflashes from tank to transformer terminal can arise—particularly on distribution systems—and these impose rectangular waves on the windings; they could only be avoided by putting the absorber in the transformer tank, a process limited to new installations. It is admitted that complete protection is exceedingly difficult to achieve, and other methods are probably equally incapable of providing it.

Mr. J. E. L. Robinson: Two very important properties of the surge absorber are its effect as an amplitude co-ordinator and its improving performance with increasing severity of lightning conditions. For every particular system voltage and surge absorber these points can be quantitatively examined. In what follows the conditions are considered for a typical case of a 110-kV system and a surge absorber similar to those employed by the authors. Closely similar results obtain, of course, for any other system voltage.

In practice the amplitude of the impulse voltage incident on an unprotected transformer or on the line side of a surge absorber is governed by the flashover characteristics of the insulators and their gap settings. On a 110-kV system the 50-cycle crest dry flashover value will be about 350 kV, which is equivalent to a 25-in. rod-gap (the impulse flashover characteristics of insulators and rod-gaps are now fairly well established down to times of the order of 0·5 microsecond). Fig. C has been prepared from published information* and shows the flashover voltage for varying times-to-flashover of 110-kV insulation on a linearly rising positive voltage. This gives the limiting amplitudes of steep-rising abrupt-collapsing voltages which could be incident on a connected transformer in the absence of surge-absorber protection.

When the absorber is in circuit the voltage on the protected transformer rises more slowly, and its amplitude is consequently always instantaneously less than the terminal flashover value. Fig. D shows the connection between the percentage of flashover voltage which appears on the protected side and the time to flashover. This curve was prepared analytically for a linearly rising applied voltage.

It is clear that the shapes of the curves shown in Figs. C and D in the short-time region tend to counteract each other. Actually Fig. D is the stronger factor, and the combined curve falls for the shorter times-to-flashover. This curve is plotted in Fig. E. The information given in Figs. C and E is also shown as AB in Fig. F, where it is plotted as protected voltage against flashover value of applied voltage. The point B corresponds to 0·25-microsecond flashover. The portion OA of the curve relates to formed waves not causing flashover. The complete curve OAB is then practically the envelope of the amplitude on the protected side for any terminal condition.

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* *Journal I.E.E.*, 1937, vol. 80, p. 348.

* J. H. Hagenguth: *Transactions of the American I.E.E.*, 1937, vol. 56, p. 67; P. Sporn and I. W. Goss: *ibid.*, 1937, vol. 56, p. 245.

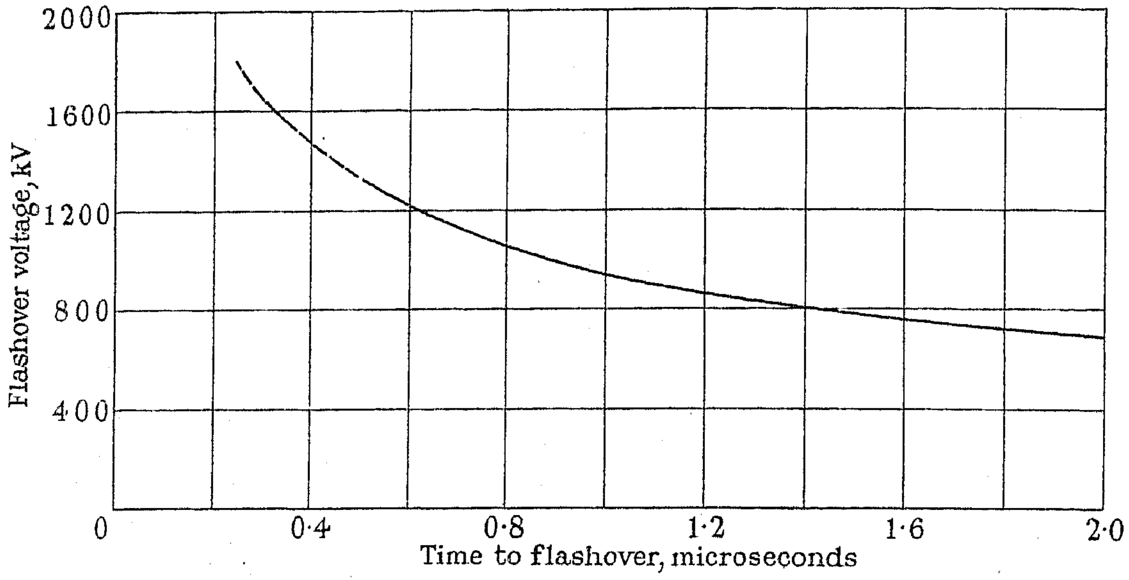

Fig. C

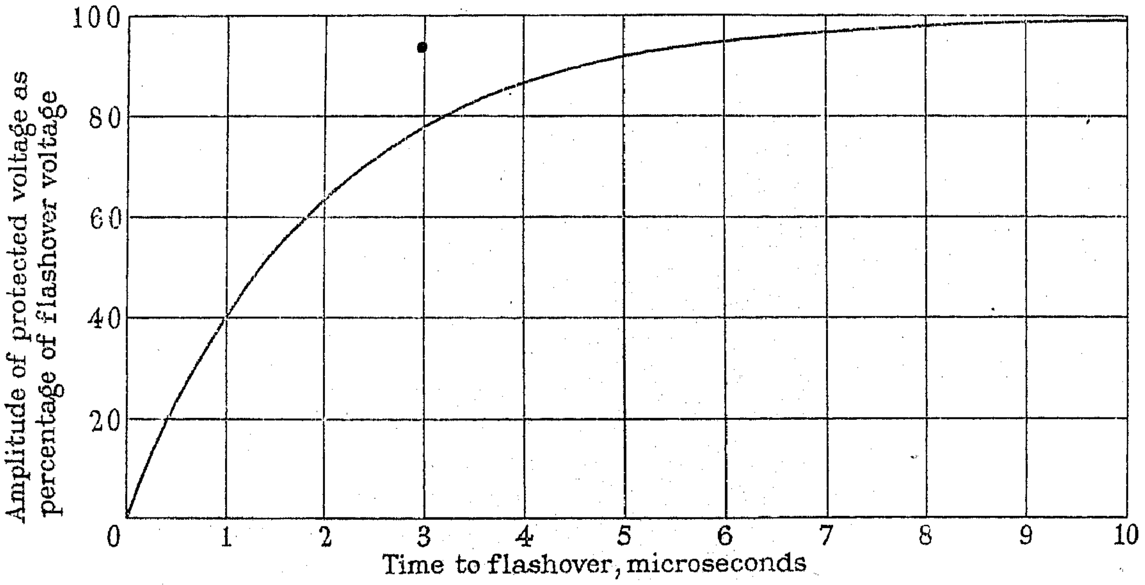

Fig. D

Expressed in this form the co-ordinating effect of the surge absorber on the amplitude of the protected voltage is clearly shown. The point A approximately corresponds to the minimum 1/50-microsecond wave flashover value of the insulator. Accordingly, the voltage amplitude on the protected side never exceeds the minimum 1/50 flashover voltage of the insulator, no matter how severe the line conditions may be. This then is the maximum stress to which the major insulation of a protected transformer could be subjected.

The point A, however, does not in general correspond to the worst axial stressing which can obtain on the protected transformer; because when flashover occurs the wave-front on the protected side no longer has the constant value equal to the normal flattening of the absorber, but is instead practically equal to the time to flashover. Since the relative axial stressing of the transformer is greater the shorter the wave-front, this factor partially offsets the falling shape of the curve AB.

Fig. G shows the relation between the wave-front of the terminal voltage and the relative axial stressing for a typical 110-kV transformer. This curve was obtained experimentally and is similar in shape to that shown in the authors' Fig. 12, except that account has been taken of the shift of the region of maximum stress with varying wave-front. The 1/50-microsecond wave impulse stress is taken as unity.

By combining Figs. F and G, the complete performance of the surge absorber for varying time-to-flashover is obtained. This corresponds to the portion A′B′ of the curve in Fig. H. In drawing this curve each amplitude

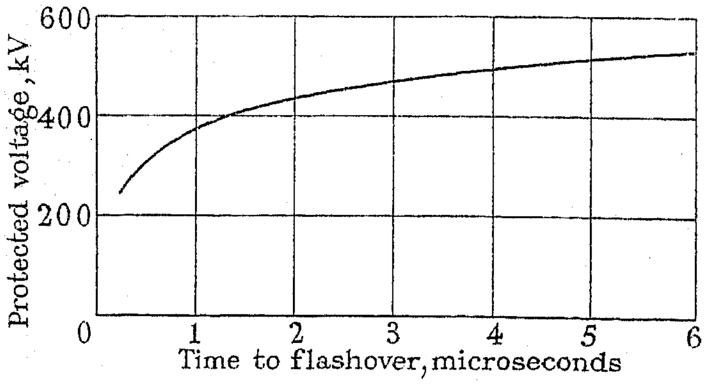

Fig. E

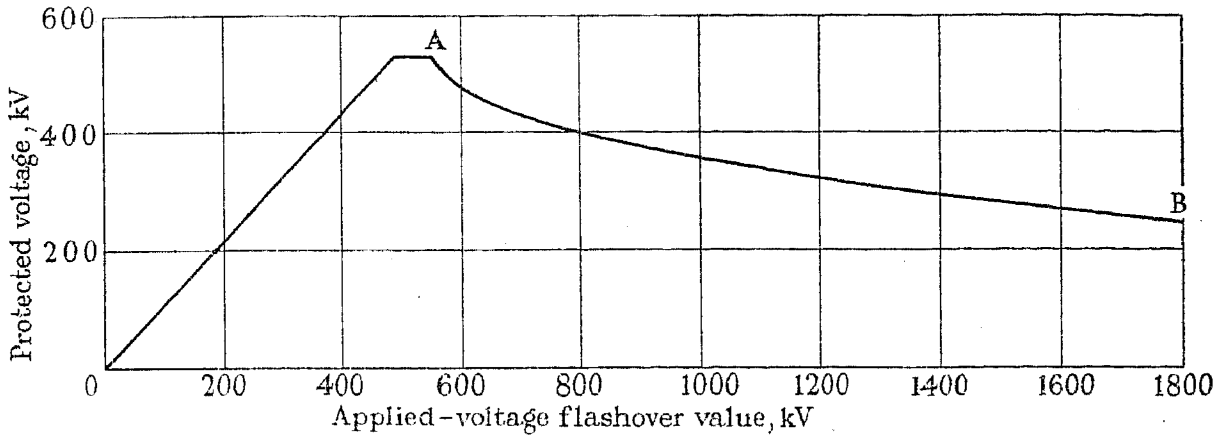

Fig. F

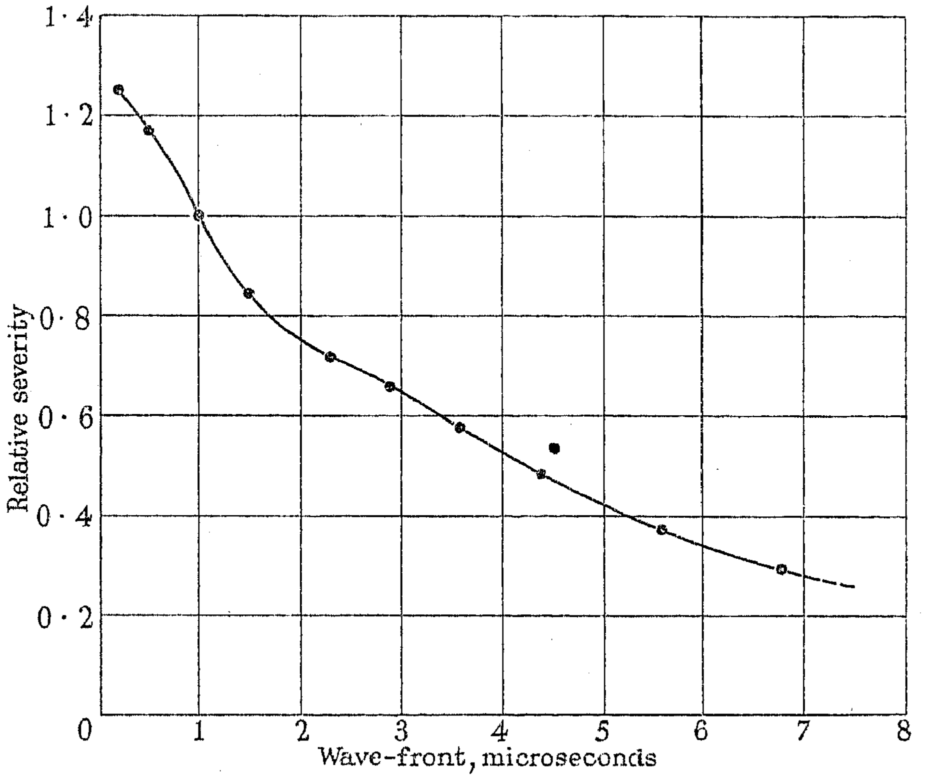

Fig. G

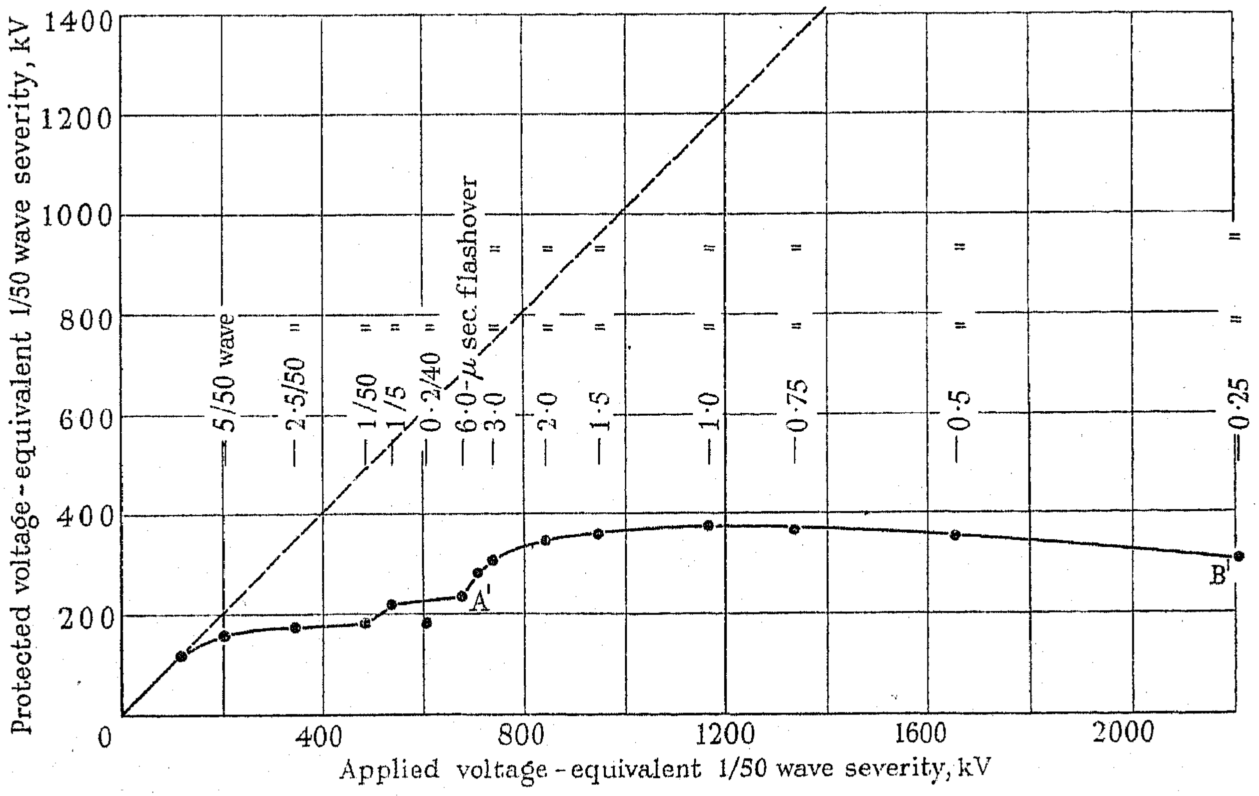

Fig. H

and wave-shape is expressed as the equivalent amplitude of 1/50-microsecond impulse which would produce the same axial stressing in the transformer. The point B′ corresponds to 0·25-microsecond flashover.

The whole curve of Fig. H is composite. For applied voltages of less than about 680 kV equivalent severity formed waves are the more severe. The region OA′ relates to these. The whole curve OA′B′ accordingly represents the limiting axial severity on the protected transformer for each condition of terminal severity. Without surge-absorber protection the performance on the basis of Fig. H would, of course, be the line of 45° slope which is shown dotted.

The flat nature of the curve of Fig. G is an exceedingly important property of the surge absorber. In the case considered, the greatest axial severity which could arise on the protected transformer is equivalent to a 375-kV 1/50-microsecond wave, and it occurs for flashover at about 1 microsecond.

From Figs. F and H it follows that provided only the transformer has a 375-kV 1/50-microsecond axial impulse strength and a 530-kV major insulation strength—and these are not unreasonable requirements in a 110-kV transformer—then the addition of a surge absorber renders it virtually surgeproof. In the absence of the absorber under the 0·5-microsecond flashover conditions the transformer axial strength would require to be 1 660 kV equivalent 1/50-microsecond wave, and its major strength some 1 350 kV, in order to be safe. Under such conditions, therefore, the absorber would be equivalent to a 4·4-fold increase in the axial strength of the transformer and would limit the stress on the major insulation to some 40 % of its unprotected value.

It is also clear how the ratio of protection improves progressively with increasing severity. Insulator characteristics in the region of 0·25-microsecond flashover at high voltages are not yet very accurately determined, but the falling levels of Figs. F and H in this region demonstrate that the real conditions could be considerably worse (i.e. Fig. C could rise more steeply in the short-time region) than the present measurements show without jeopardizing the above features of the absorber performance. Again, it is always possible that lightning voltages effectively reaching flashover value in even less than 0·25 microsecond may be proved to occur. In that possible event the downward trends of the curves at B and B′ strongly suggest that the level of protection given by the surge absorber would be maintained into that region. This property of the surge absorber in maintaining a uniform level of protection independent of the severity of known or even unknown terminal conditions is unique and is not, it is believed, shared in any measure by any other protective apparatus.

In presenting the foregoing data, refinements of argument have perforce been omitted. Several relatively minor factors exist, some tending to increase and some to decrease the severity. One major point in connection with Fig. G requires comment. It has been implicitly assumed here that in the unprotected cases a steep collapse produces the same stress as would a similar steepness and amplitude of front on a formed wave. In actual practice, however, an oscillation on flashover contributes to the total collapse voltage and on that account increases the severity. In addition, the collapse usually coincides somewhat fortuitously in an additive manner with peaks of opposite polarity on some of the relevant intercoil voltages, and this also tends to increase the severity. Again, tending to mitigate the effects of these two factors, for very short times of flashover some reduction of amplitude occurs as the short pulse of axial voltage penetrates to the region of normal insulation where the strength of the transformer is generally determined.

These factors do not arise in computing the performance with the surge absorber, since this eliminates the severe oscillation, slows the rate of collapse, and lengthens the back of the collapse to a few microseconds. The ordinates of the points in Fig. H are therefore not affected. On the other hand, the abscissae will be distorted by these factors to some extent, being rather more severe than is indicated for the longer times to flashover and less severe for the very short ones. Since these considerations only complicate the argument, and since they do not affect the level of surge-absorber performance, they have been neglected here. Their omission has corresponded to a pessimistic calculation of the overall surge-absorber performance.

Mr. W. Fennell: In our area the cost of protecting transformers by almost any means on a widely spread high-voltage distribution system is not justified. For example, surge-absorber protection for a small transformer costs about as much as the transformer itself. Moreover, the surge absorber adds to the obstructions which already prevent easy access to the pole-mounted transformer, and we know little of its performance beyond what the makers publish.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Dr. J. L. Miller and **Dr. J. M. Thomson** (*in reply*): The keynote of the paper, as Mr. Norris has pointed out, is the emphasizing of the greater importance of axial stresses in comparison with the radial stresses in transformer windings. The emphasis on this point has apparently not been challenged except by Dr. Allibone, Mr. Holbrook, Mr. Hansel, and Dr. Stritzl, and even then in each case not only has the challenge been tempered with extreme caution but no substantiated arguments have been put forward such as have been advanced in support of our beliefs in the paper, and by Mr. Robinson in the discussion. Merely suggestions regarding modes of major insulation breakdown have been given (only one of which, i.e. flashover from an open neutral, appears to be backed up by any citation of operating experience or, as Dr. Allibone puts it, " the fickle index of public opinion "), and we therefore feel justified in concluding that the dissertations of the dissentient voices must simply be considered as a healthy desire to criticize. If the truth of the matter were other than we think, then that truth would surely be demonstrable by argument, and the lack of such argument on the part of these critics must indicate, after all, that our views have not really been challenged at all.

It is appropriate here, however, for us to mention on our part that we do not consider that radial stresses are of no importance, but we certainly do say that such experience as we have had personally—and in reply to Dr. Allibone it covers the deliberate breaking-down of a large number of transformers manufactured by two different factories, the one designing to English standards and the other conforming with American practice, the examination of some transformers actually damaged by lightning, and the perusal of certain reports on other transformers damaged by lightning—goes to show that only an unimportant percentage of transformers are broken down by major insulation failures. It is difficult to account for the conflict of opinion, but from our experience we seriously suggest that damage and deterioration in the axial direction of the insulation between h.t. and l.t. windings arising from an excessive transient voltage between coils may lead to a breakdown through this insulation on some subsequent high-amplitude but not necessarily steep-fronted surge. To call such a breakdown primarily a major insulation failure would thus be incorrect. The point, of course, has been mentioned in the paper, but we emphasize it now.

Regarding means of minimizing and controlling axial stresses other than by surge absorbers, the discussion has brought little new information to light. Perhaps the most interesting references are those made by Dr. Allibone, Mr. Bolsterli, and Mr. Holbrook. Dr. Allibone refers to the use of condensers connected between sections of a winding. In reply we would say that while we agree that such an arrangement certainly does a great deal to mitigate the evils of axial stressing, our contention that it gives rise to space and insulation difficulties has not been questioned. Mr. Bolsterli sponsors the external condenser, and to him we would state that its capacitance has to be very great in order to be effective under all conditions. Mr. Holbrook favours the shielded transformer. While we agree that a non-resonating design is satisfactory in minimizing axial stresses, the degree of safety attained depends on the closeness with which the initial distribution approaches uniformity. It was with interest, therefore, that we noticed on a slide shown by Mr. Holbrook that he, at any rate, does not always apply the principle to the fullest extent—presumably because of additional insulation difficulties or excessive increase in size, or for reasons of economy.

There is a point in connection with non-resonating transformers, however, to which we would draw attention. There is no feature in this type of transformer that makes for other than a slight reduction in maximum radial insulation stress and therefore, in the face of some engineers' rather summary condemnation of the statement that axial stresses are of greater importance than radial ones, we are at a loss to understand how those engineers can advocate the surge-proof properties of the non-resonating transformer. The fact that shielded designs appear to be more resistant to surges than normal designs simply supports our view that axial stresses are the more important. Further, those who have fears for major insulation should realize that the risk of breakdown is obviously a maximum under direct or nearby direct-stroke conditions, when the corresponding radial stresses may be at least about 4 times those arising under the worst travelling-wave conditions. Here the non-resonating design is no palliative, but the surge absorber, designed primarily as a wave-flattener, has the inherent property of reducing very considerably the major insulation stresses. In fact, as Mr. Robinson has shown, these stresses are approximately limited to the 1/50 travelling-wave stresses.

In concluding these general remarks we feel that there are perhaps three other main aspects of the paper which break new ground. The first is the description of the form of the axial-voltage distribution curves, a form which varies little with transformer kVA and voltage rating or with the test conditions. The second is the demonstration of influence of reinforcement on the voltage distribution, while the third is the description of the design and operation of circuits simulating various kinds of direct-hit conditions. None of these has received any adverse comment or criticism and we are accordingly gratified.

We shall now deal specifically and in detail with the various comments raised. We thank Dr. Allibone for his appreciation of our technique in measuring axial gradients. In reply to the other comment in his first paragraph, we would say that the substitution of tracings of oscillograms in place of their photographic reproductions considerably simplified the printing and assembly question. Our technique has, of course, already been illustrated by the inclusion of numerous oscillograms of both intercoil and interturn voltages in previous publications.

Dr. Allibone also asks us whether a surge absorber can deal with a direct stroke without suffering harm, and in reply we would state that the surge absorber is designed to withstand the most onerous conditions which we have envisaged as arising from direct hits. Now the amount of major insulation depends on the maximum voltage permitted by the bushing, which in turn depends on the rate of voltage rise and the impulse ratio. Using, therefore, the maximum figures that have been tentatively put forward by various workers from time to time for the rate of rise of voltage in the lightning channel, and using safe values of the impulse ratio and other relevant factors, the major insulation can be suitably designed. Further, the axial insulation presents little extra difficulty since there are no severe voltage concentrations, as in a transformer winding, owing to the fact that the value of α in a surge absorber is very small; this is illustrated in Fig. J, which shows an almost straight-line gradient distribution curve. Thus the absorber can be readily, and is, designed to withstand direct hits in comformity with the generally accepted characteristics of lightning. If, of course, later research indicates that the lightning channel has properties different from those tentatively accepted, or if the conditions are more severe than those assumed, the position will naturally have to be reviewed.

Regarding the question of the thermal losses, a small 30-ampere 12-kV surge absorber would have a 50-cycle loss of about 60 watts, i.e. 0·017 % of the throughput kVA; while in a 300-ampere 66-kV unit the loss would be about 4 kW, representing 0·02 % of the throughput kVA. Apart from impulse tests carried out as type tests, all absorbers are tested between terminal and tank at $2\frac{1}{2}$ times the line voltage, and in addition the temperature-rise and overload capacity tests are similar to those carried out on transformers.

Dr. Allibone, referring to the question of flashover at an open neutral, draws the conclusion that long-wave high-amplitude surges must arrive at transformers quite frequently. The greatest possible voltage occurring at an open neutral is twice the terminal voltage, and to obtain this a very long incident wave is required. From our reading of the available statistics it would appear that such waves with high amplitudes do not often occur. Mr. Bolsterli sums up the situation well when he states "according to statistics on lightning, waves of very large amplitude are as a rule short, and vice versa, the charge only rarely exceeding 0·03 coulomb." The alternative suggestion, therefore, is that the flashovers to which Dr. Allibone refers are caused by direct or nearby direct strokes where the shorter surges incident on the transformers may have amplitudes very considerably greater than those due to travelling waves. As shown in Sections 5(*c*) and 5(*e*) of the paper, the surge absorber reduces the amplitude of the terminal voltage here so that the neutral voltage is also reduced.

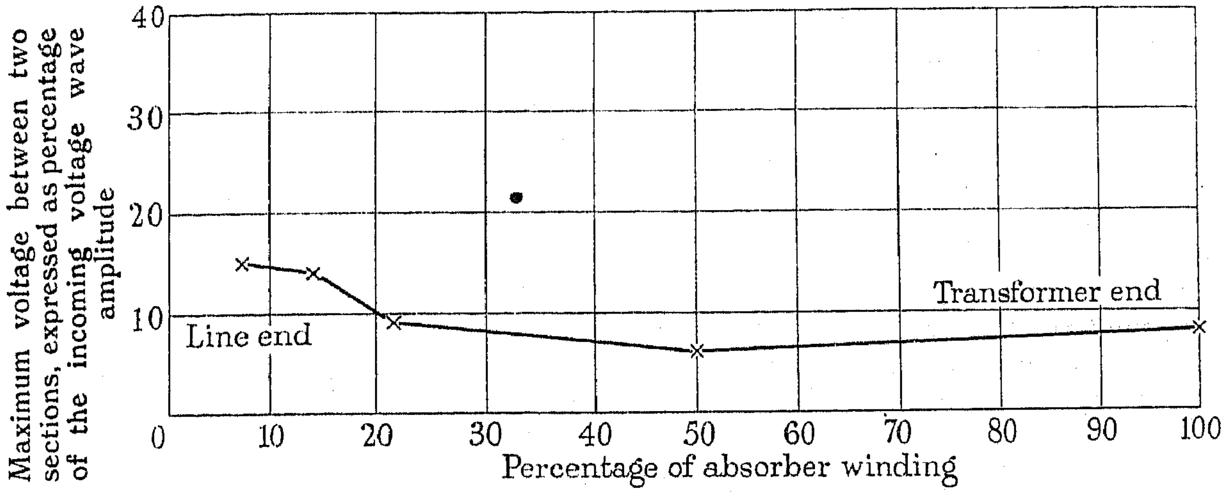

Fig. J.—Voltage distribution curve of a surge-absorber winding under 0·2/40 travelling-wave conditions.

Dr. Allibone also suggests that under direct-stroke conditions and with high earthing resistances a flashover across the line-end terminal of a surge absorber would be followed by another flashover across the transformer end terminal from the tank to the conductors. In reply we would say that there is no danger from this cause since, as Dr. Allibone himself suggests, it is the practice to bond the surge-absorber and transformer tanks together in high-resistance terrains, and in Canada there are some hundreds of surge absorbers operating in this manner with very high earth resistances without trouble. In fact, the bonding of the tanks is fairly general Canadian practice even when earth resistances are low. In referring to the trouble-free operation of surge absorbers in Canada—and, of course, we could quote numerous other cases of satisfactory performance in all the lightning districts of the world—we realize that Dr. Allibone is loath to accept the results and teachings of operating experience. This, in our opinion, is tantamount to believing that ability to make unbiased observation is never given to the user of apparatus. It is common experience that after initial development the prospect of future usefulness of apparatus or devices is doubtful if their performance in actual work is unsatisfactory or prejudicial to the operation of existing equipment, and surely the converse holds.

The point which Dr. Allibone has raised is, however, of interest and warrants further comment. Fig. K(*a*) shows in schematic form a surge absorber protecting a transformer C_e when the condition of non-bonding prevails. T represents the surge-absorber tank, "m" and "n" the flashover paths across the line and transformer-end insulators respectively, and R_e the earth resistance. When a direct stroke occurs at S, the various voltages are shown in Fig. K(*b*), *a* denoting these voltages up to the instant of flashover and *b* after the instant of flashover. It will be seen that there is a sudden partial collapse of the line terminal voltage at the instant of flashover, due to the sudden inclusion of the earth resistance. After the instant of flashover, the schematic circuit for the surge absorber essentially becomes that shown in Fig. K(*c*), the gap "m" now being in effect a short-circuit. Under these conditions, the voltage across "n" will simply be that obtained from the short shaded part P of Fig. K(*b*) after passing through the absorber; that is, P becomes "p" in Fig. K(*d*). Since the original flashover value was "f," the amplitude "h" of the voltage across "n" will be considerably lower (since P is short) and will occasion no flashover across "n." There is no danger, therefore, of a flashover across the surge-absorber bushing, and Dr. Allibone is wrong in his conclusion.

This, however, is not the whole story. The voltage across C_e, the transformer, due to the presence of the earth resistance, will have the general shape shown in Fig. K(*e*), and if the earth resistance is not greater than something of the order of 60 ohms this voltage will not have an amplitude great enough to cause flashover across the transformer bushing; further, the very small steep-fronted component will be unimportant. If the earth resistance is greater than about 60 ohms, the amplitude of the transformer voltage will also be greater and there will then be risk of flashover at the transformer. Bonding together of the two tanks, however, means that in schematic form C_e ceases to exist separately as in Figs. K(*a*), and K(*c*), and can then be considered as being lumped with C_1. The voltage across the transformer is then simply as shown in "p" of Fig. K(*d*), and there is no danger of flashover. In order to simplify the explanation we have represented the various voltages diagrammatically, but they can be considered to be roughly relative.

With regard to Dr. Allibone's query as to the value of the output wave-front from a surge absorber for which we design, we would say that this question is dealt with in Section 3(*c*) of the paper. He is quite in error, of course, in quoting a value of 1 microsecond, and he has obviously misread Curve (*c*) for Curve (*b*) in Fig. 2; the values given there actually range from 4·2 to 5·5 microseconds. Condenser performance was illustrated in the paper because its object was to discuss all relevant wave-flatteners. Condensers are, of course, used to a not-inconsiderable extent, as Mr. Bolsterli points out. In reply to Dr. Allibone's remark about the absorber he tested, we would say that absorbers designed in accordance with the principles laid down in the paper do not have the characteristics previously found by him. In this connection the correctness of our own findings is confirmed, as Mr. Norris points out, by the 1937 Report of the National Physical Laboratory.

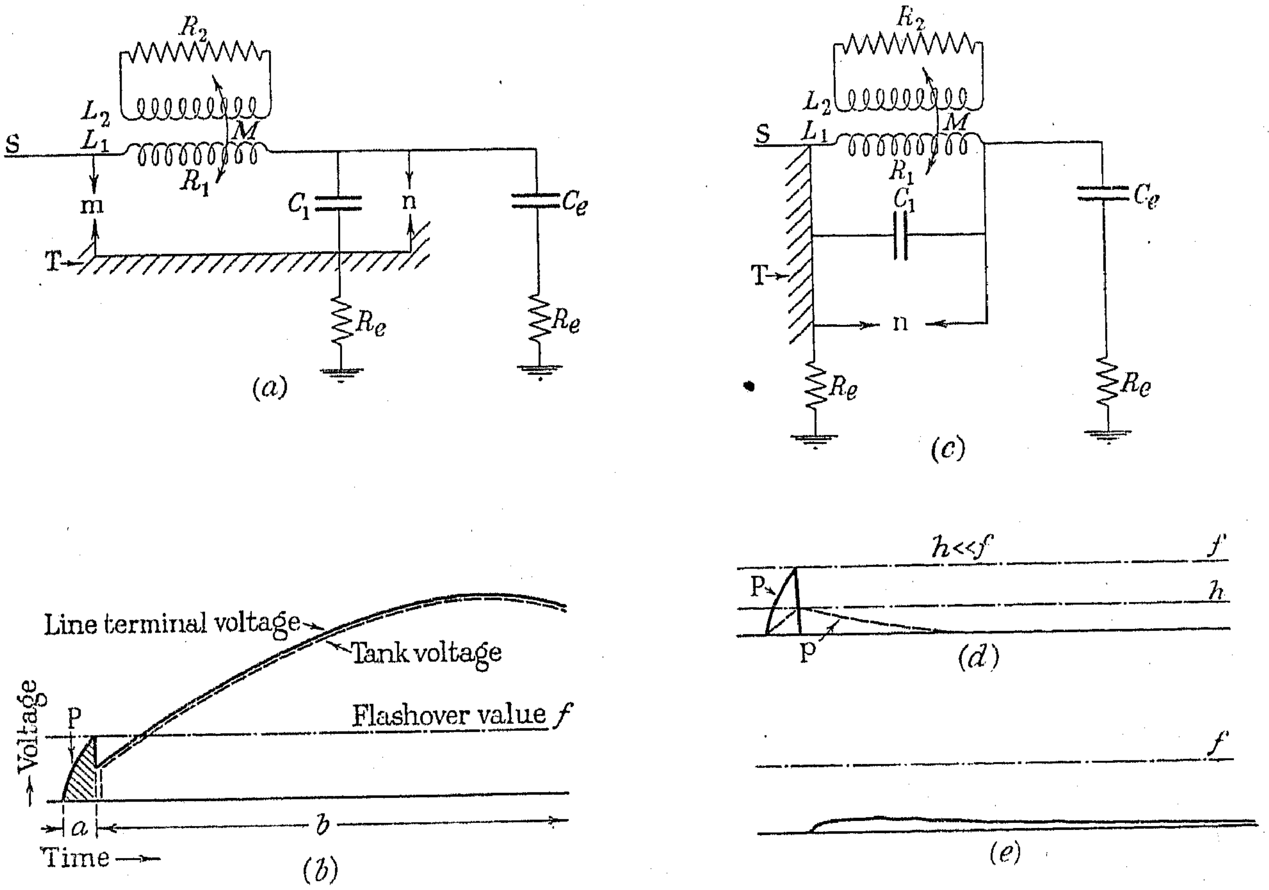

Fig. K

Dr. Allibone also gives a list of cases where he suggests that the absorber would not be effective. Immediately one can state that all the troubles he enumerates are obviated by an absorber if these troubles are caused by direct or nearby direct strokes, or by short, chopped travelling waves. We have stressed this point in replying to Dr. Allibone's separate remarks about open neutrals, and our reply there applies with equal force here. As will be evident from Mr. Robinson's remarks, the absorber reduces the amplitude of all surges to at most the 1/50-wave value. Dealing with the points in more detail, he instances the case of a transformer having stronger axial than major insulation, stating that the surge absorber would give no protection here. We cannot see, however, how he arrives at this conclusion, since even in such a rare case the absorber would obviously reduce all severe overvoltages to the 1/50 value; and the fact that the axial strength might be greater than the radial does not imply that the major insulation would not withstand the maximum 1/50 wave, except, perhaps, in the case of a most extraordinary and unnatural design, where normal safety factors above the stresses arising from the British Standard test were not employed. The same remarks apply with almost equal force to the tapping-switch question, which was also raised by Mr. Hansell. Regarding re-entrant type windings, it must be remembered that the initial distribution is electrostatic (and hence almost independent of connections), and since the most important axial gradients are at maximum value initially the criticism hardly applies. Even the criticism that alternators and switchgear on the l.t. sides of transformers would not benefit from absorbers connected on the h.t. sides does not fully hold. The co-ordinating properties of the absorber would certainly be of real benefit under the severer conditions arising from direct or nearby direct strokes.

Our remarks, however, in the previous paragraph are somewhat speculative, just as Dr. Allibone's criticisms in his last paragraph are, and therefore, putting speculation on one side and calling on operating experience, we can only add that so far neither we nor our colleagues have had our attention drawn to the troubles he enumerates when surge absorbers are used.

There is no danger, as Mr. Holbrook suggests, that a surge absorber will cause a flashover at the transformer terminal. In replying to him we would first remind him that the air insulation of the line-end bushing of the surge absorber is a little greater than that of the transformer end bushing,* and secondly we would strongly criticize the figures he gives for the alteration in flashover voltage as the wave-front changes from 0·2 to 3 or 5 microseconds. One cannot generalize as Mr. Holbrook has done. For instance, if we consider travelling waves with long backs there will not be much change in the minimum flashover impulse-ratio as the front is flattened from 0·2 to 5 microseconds. Therefore incoming waves which just do not cause flashover on the line bushing will hardly have the opportunity of causing a flashover on the other or transformer bushing, for the reasons stated. With short travelling-waves there will be a greater difference between the impulse ratios of the line-end and transformer-end bushings, but here the absorber gives an amplitude reduction as shown in Fig. 16 of the paper, thus counterbalancing the effect of the greater change in impulse ratio. If there is flashover on the front of a steep wave or on a direct-stroke voltage, then we agree that there would be a marked difference in the impulse ratios of the two bushings, but here, of course, the absorber will operate with its maximum reduction in amplitude, so that no risk will be run.

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* This is obtained by the use of gaps. In other cases the terminals have considerably greater flashover values than the adjacent line insulators.

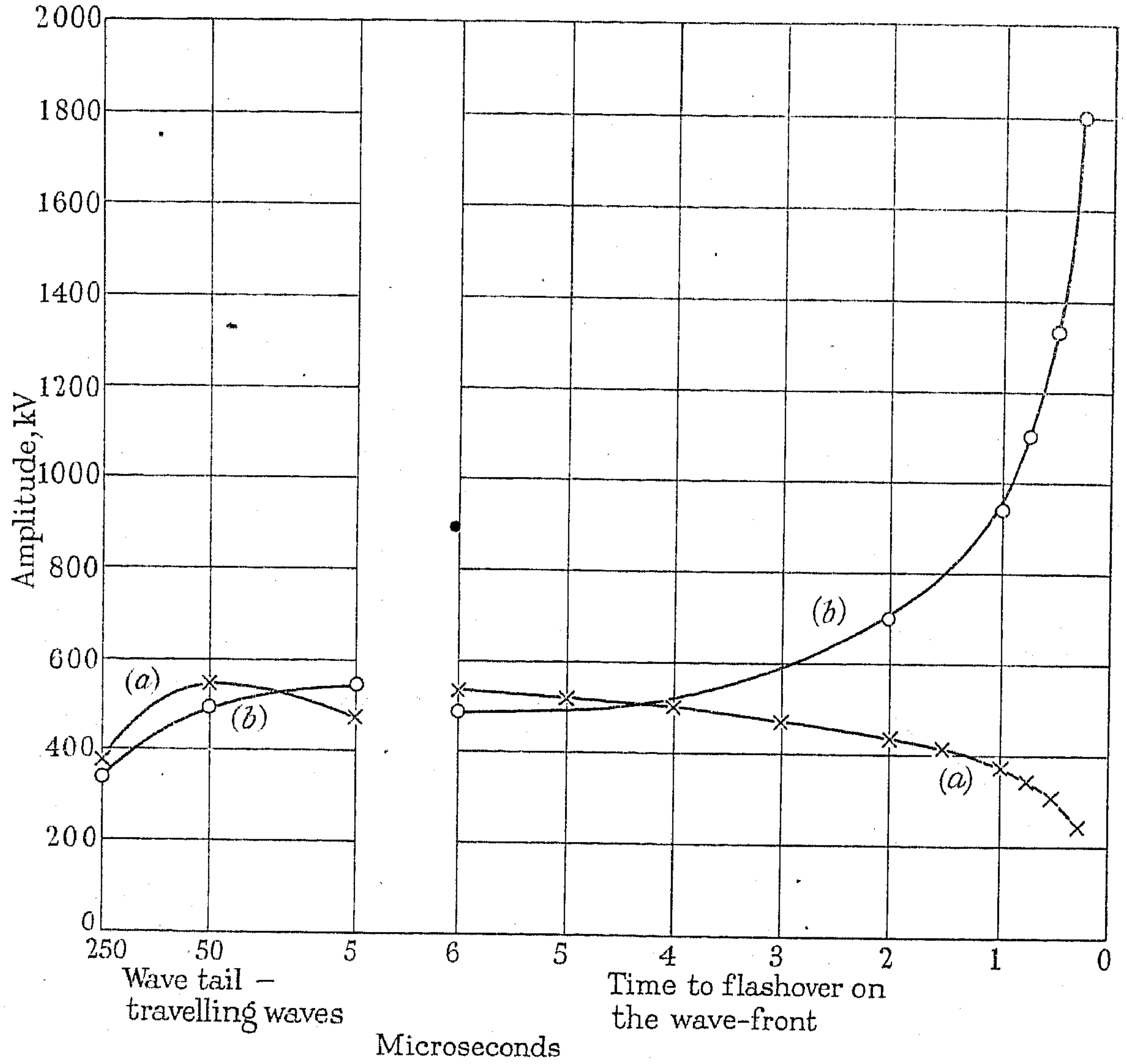

Fig. L.—Co-ordinating effect of a surge absorber.

(*a*) With surge absorber.
(*b*) Without surge absorber.

Mr. Holbrook also voices the fear that an external protective device might be found disconnnected when required. This, of course, is practically impossible with a series-connected device.

We are at a loss to understand some of Dr. Stritzl's remarks, and we can only think that he has misread parts of the paper. For a transformer to break down on the wave tail—there is no mention of it in the first reference he gives—would require a very nice adjustment between the incoming voltage and the flashover value of the bushing. Surely it could only occur very seldom with travelling waves, and never with direct strokes. We agree that the progressive shift down the winding of the point of maximum stress to which Dr. Stritzl refers takes place, but our curves certainly take this into account since they give the actual maximum gradients irrespective of time. These gradients, however, even with the steepest fronts or tails, become rapidly smaller—as the gradient-distribution curves in the paper show—as the neutral is approached, and thus on this score there is no reason why, despite Dr. Stritzl's opinion to the contrary, properly designed reinforcement cannot be of considerable benefit in greatly increasing the axial strength of a winding above that of a normally reinforced winding. We are also at a loss to understand on what grounds he concludes that a properly designed wave-flattener cannot make a transformer surge-proof; we can only refer him to Mr. Robinson's remarks and to Fig. L.

In his next paragraph he states that a surge absorber cannot safeguard a transformer against the tail of a surge. In reply we would say that in the paper we have demonstrated that tails are mainly dangerous to windings when they are steep, and Figs. 18 and 26, which he does not appear to have noticed, confirm that the surge absorber is very effective indeed here. His other points in the same paragraph are covered in our reply to Dr. Allibone.

We thank Dr. Stritzl for his interesting remarks on arresters. We agree with him, in that this principle of protection has been adopted by most of the principal manufacturers, but it certainly has not been adopted by all the principal users, which is probably more important. The operating record he gives of arresters on a certain system is a good one, but equally good records spread over several years are also available of surge-absorber performance. The limitations to the installation of arresters to which we referred were based on statements made in publications by engineers of firms manufacturing them. There is no need to include arresters between lines and earth in circuits where surge absorbers are used, but if anyone desires to do so no harm will result. To shunt a surge absorber—we presume Dr. Stritzl means connect in parallel with the inductive element—with a resistive device like an arrester would, however, be harmful. If the resistance were small in value it would impair the flattening, and in any case it would affect adversely the damping properties of the secondary winding. Dr. Stritzl also states that small pole-mounted transformers are left unprotected for reasons of economy. In reply to this we would say that in Canada we have found this to be a prolific source of business, and in fact 50 per cent of the distribution transformers emanating from our Toronto factory are equipped with surge absorbers installed in the transformer tanks.

Mr. Kilburn Scott refers to the difficulty of obtaining earths in dry or even in desert country. Presumably the only solution is to connect up the tower feet, as he suggests, with counterpoise connections; to connect, however, the counterpoise system with some oasis would not be necessary, and in addition would serve no useful purpose from the transient point of view since the true earth would then be too remote. We are not qualified, however, to discuss the question of the prevention of the theft of copper conductors by African natives.

Mr. Kilburn Scott's remarks on furnace transformers are very interesting. It is evident from what he says that the breakdowns were due to the rapid change of voltage, and since the voltages produced would not have high amplitudes the simple inductance coils he used would give, as they did, satisfactory protection.

Mr. Robinson's first set of remarks are valuable in that they provide an alternative argument to that given in Section 3(*a*) of the paper; in fact, anyone studying the subject would be well advised to consider this contribution to the discussion as part of the paper and to read it in conjunction with Section 3(*a*).

Now it is evident from a study of the oscillograms in the paper that as surges get progressively more dangerous, so the surge absorber gives an ever-increasing measure of protection until, with severe direct strokes which cause flashover early on the front, very considerable amplitude reduction is attained. The surge absorber is thus an effective amplitude co-ordinator, and this point has been very effectively worked up by Mr. Robinson in the series of curves shown in his second contribution to the discussion. His conclusions are demonstrated in Figs. F and H and confirm quantitatively what was qualitatively evident from the paper.

It is interesting and important, however, to take the matter one step further, and therefore Fig. L, derived from Mr. Robinson's series, is here included. Along the first part of the abscissa is plotted the travelling-wave tail-length (with a fixed steep front) and along the second part, after the point of discontinuity, the time to flashover on the wave-front; the latter covers the travelling-wave flashover and the direct stroke range. Voltage amplitude is given on the ordinate scale, and the two lines (*a*) and (*b*) respectively give the voltage with and without a surge absorber for the conditions specified. Curve (*a*) indeed shows that the surge absorber is an effective amplitude co-ordinator.

In reply to Mr. Shipley, we would say that we do not know of any modern report giving the number of transformer breakdowns per annum. Reports on trouble experienced by the various operating authorities in the United States are, however, continually appearing in papers published in *Electrical Engineering*, and we would refer him to these. In reply to his other comment, we would say that surges certainly pass from the h.t. to the l.t. windings of transformers, the ratio of the voltages being of the same order as the turns ratio. Alternators having weak insulation to earth in the slots may therefore break down. The transfer is electromagnetic and, except perhaps for a low-amplitude steep-fronted kick at the instant of impact, the l.t. surge voltage is not steep.

We thank Mr. Bolsterli for his very valuable contribution to the discussion. It is interesting to us because it broadly illustrates the trend of thought of certain Continental engineers, a trend which embraces an understanding of the usefulness of a wave-flattening device. The particular wave-flattener sponsored by Mr. Bolsterli is the condenser, but he very frankly states that operating experience must, in the last analysis, decide the place of the condenser as a surge-protective device. We wholeheartedly agree with that view. His phrase " in the last analysis " is particularly pertinent in view of what we have said before about operating experience.

Now the largest condenser we tested had a capacitance of $0 \cdot 042\,\mu$F, and while it was effective, as Mr. Bolsterli points out, when used in the circuits shown in Figs. 24 and 34(*b*), it was not effective in other cases. Two instances are those shown for Figs. 29(*b*) and 37(*b*), Section 5(*e*), where we state that the distribution curves were unsatisfactory. Now if a condenser has a very large capacitance indeed it ought to provide adequate protection. We find that $0 \cdot 042\,\mu$F is not large enough. Mr. Bolsterli states that something of the order of 10 times bigger has proved satisfactory in practice. We accept that statement, but we still wonder whether it would be satisfactory, say, in the tests described in Section 5(*e*)(ii*a*).

We would, however, make three comments. First, we wonder how the cost and size of a $0 \cdot 44$-μF condenser compare with those of a surge absorber. Surge absorbers are not expensive and in general cost about 7 % to 30 % of the transformer price (and not, as Mr. Fennell suggests, the same amount as the transformer), the latter figures pertaining to a few surge absorbers in the very low-voltage high-current range. And, of course, tappings on the condenser section of the surge absorber can also be made to perform the function of a potential transformer just as in a plain condenser.

Secondly, the method referred to by Mr. Bolsterli of diverting a flashover to a co-ordinating gap some distance away has advantages, even with the smaller condensers. We show this ourselves for travelling waves in Figs. 24 and 27. Also the greater the distance between the flashover point and the condenser, the better the protection attained. The beneficial effect, however, would be nullified if a stroke and a flashover occurred at some point on the line between the co-ordinating gap and the condenser —the nearer the flashover to the condenser the less the protection. Similarly, a stroke to a conductor at mid-span of an unguarded system, so that no flashover could occur at the point of incidence, would permit considerable rise in voltage at the condenser, with grave risk of flashover there, until opposite-polarity reflections returned from the co-ordinating gap. We conclude, therefore, that the suggestion may not be generally applicable. The use of the earth resistance between the condenser and the gap earths as a damping resistance, while novel, is also surely unreliable and variable with rainfall. Lightning is usually accompanied by rain, when a lower-resistance path between the two earths might be formed, with consequent reduction in damping.

Thirdly, another factor comes into prominence when condensers having large capacitances are used. This is the inductance of their connecting and earth leads, which gives rise to a sharp peak or kick on the voltage wave across the condenser, at the instant of impact, of practically the same steepness as the incoming wave. We had to take considerable care in order to eliminate it even in the laboratory, and we finally concluded that the phenomenon was of sufficient practical importance to warrant our employing a length of conductor corresponding to that which might occur in practice; no doubt, in many cases the length in practice would be greater than we used. We thus retained some peak and its development is evident in Fig. 28 of the paper. While in the paper this peak did not contribute to the maximum transformer gradient, because of the heavy line-end reinforcement of the winding and because its short duration did not permit of its penetration to the point where the gradient occasioned by the normal portion of the surge voltage was a maximum, we can visualize cases where it would be important.

We see absolutely eye-to-eye with Mr. Bolsterli when he stresses the co-ordinating effect of a wave-flattener. This idea, while evident from the paper, has been expanded by Mr. Robinson for the case of the surge absorber and we have already referred to it.

We agree that the performance of the condenser can be accurately predicted by calculation. One of us (J. L. M.) has already treated this subject for waves of the $E(\epsilon^{-at} - \epsilon^{bt})$ type in a paper* published a long time ago. As will be evident from the Appendix in the present paper, the performance of the surge absorber can also be accurately predicted.

Mr. Savage's remarks on operating experience are exceedingly interesting and valuable, and we would draw Dr. Allibone's attention to them. They are similar to numerous other reports we have had privately. With reference to Mr. Savage's question about the line-side potential of a surge absorber, we would say that the voltage here is essentially no different in magnitude from that which would have appeared at the transformer without surge-absorber protection. This is accounted for essentially by the fact that both from an unprotected transformer and from a surge absorber the reflected wave is of the same polarity as the incident wave. Fig. M illustrates the point for a surge absorber similar to that described in the paper.

Mr. Savage quite rightly takes us to task for omitting the surge-absorber earth connections from some of the diagrams. Actually we only included a dotted outline sketch of the absorber, so that its position in the circuit would be quite clear. The earth connections are, of course, required. Mr. Savage also refers to the question of earth resistance. Our remarks to Dr. Allibone will give him a good deal of information, and in reply to his specific query we would say that resistances of the order of 0·5 to 20 ohms will not in practice affect the performance of the surge absorber in any way.

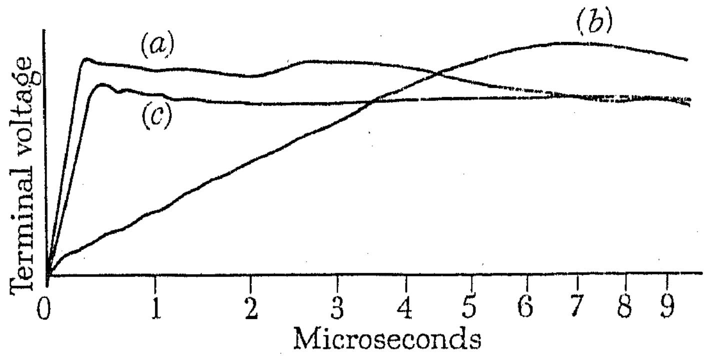

Fig. M

(*a*) Incident wave.
(*b*) Output wave from surge absorber.
(*c*) Voltage on line side of surge absorber.

Mr. Gibson asks us to show a typical distribution curve of the voltages to earth inside a winding when the terminal voltage is of short duration. In answer to his request we therefore include Fig. N, which gives the envelope of the maximum voltages to earth in a 33-kV 2 000-kVA transformer having usual reinforcement when the terminal voltage wave is a 0·5/0·6 one. This represents the condition arising from a travelling wave chopped on the front or from a direct stroke.

In reply to the point raised in Mr. Gibson's second paragraph, we would say that we have had confirmation on numerous occasions when testing normal transformers to destruction that they were weakest in a region below the top reinforcement, and in this connection during the reading of the paper we exhibited a slide which showed an actual breakdown in this region caused by lightning in service. We reproduce this slide now in Fig. O for his information.

Prof. Marchant refers to an investigation* which one of us (J. L. M.) carried out under his direction about 13 years ago. It is interesting to record, however, that many of the effects then noticed do not appear to exist when the

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* *Elektrotechnik und Maschinenbau*, 1932, vol. 50, p. 281.

* *Proceedings of the Royal Society*, A, 1926, vol. 111, p. 604.

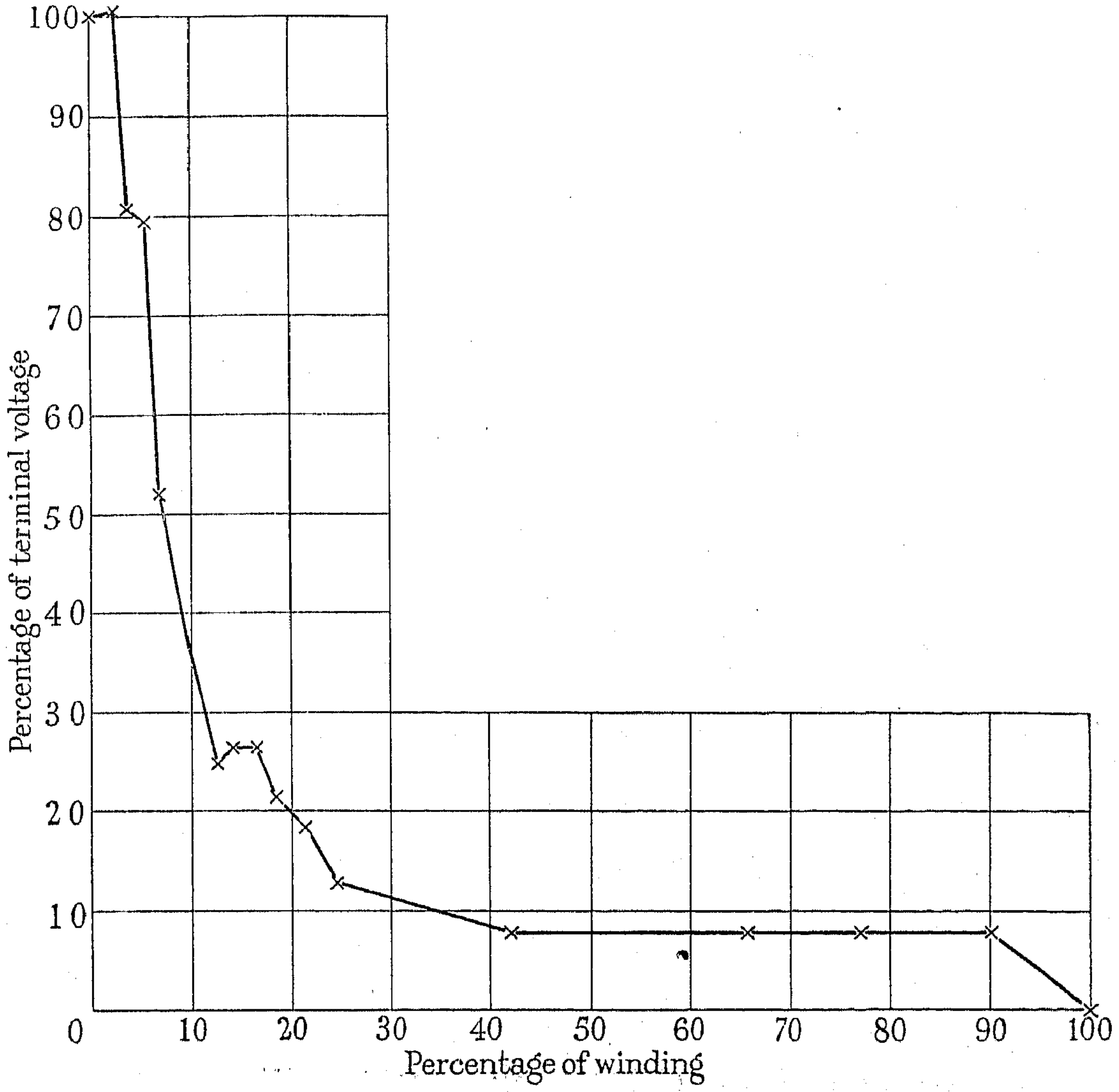

Fig. N.—Envelope of voltages to earth in a transformer winding under 0·5/0·6 chopped-wave conditions.

equivalent frequency is of the order of 1 million cycles per second or more.

We agree that lightning flashover, which may shatter insulators and may often put a line out of commission for relatively long periods, is a very serious problem, and Prof. Marchant instances the Colenso–Pietermaritzburg Railway. It is this side of the lightning question, of course, which has given rise to the development of de-ion gaps, Petersen coils, and the counterpoise, and has urged forward the understanding of the role played by the earth wire.

Prof. Marchant's remarks about our oscillograph and our technique are much appreciated. Our strong position in this field is undoubtedly due to the fact that our management initiated these researches very early on, and ever since we have had their constant encouragement.

Prof. Marchant refers to the inadequacy of the undamped inductance and then goes on to deal with the effect of sustained very-high-frequency oscillations on dielectrics. Very little is as yet known about the latter subject, and the information which Prof. Marchant is continually amassing will be of great value. The distribution along an insulator string is very similar to the initial distribution along a coil stack, because both distributions are capacitive.

Mr. Hansell raises the question of the voltages to earth in a transformer winding. Our reply to Dr. Allibone, however, essentially covers his queries. He also refers to two waves of like polarity arriving simultaneously at two phases of a delta-connected transformer, and quotes the

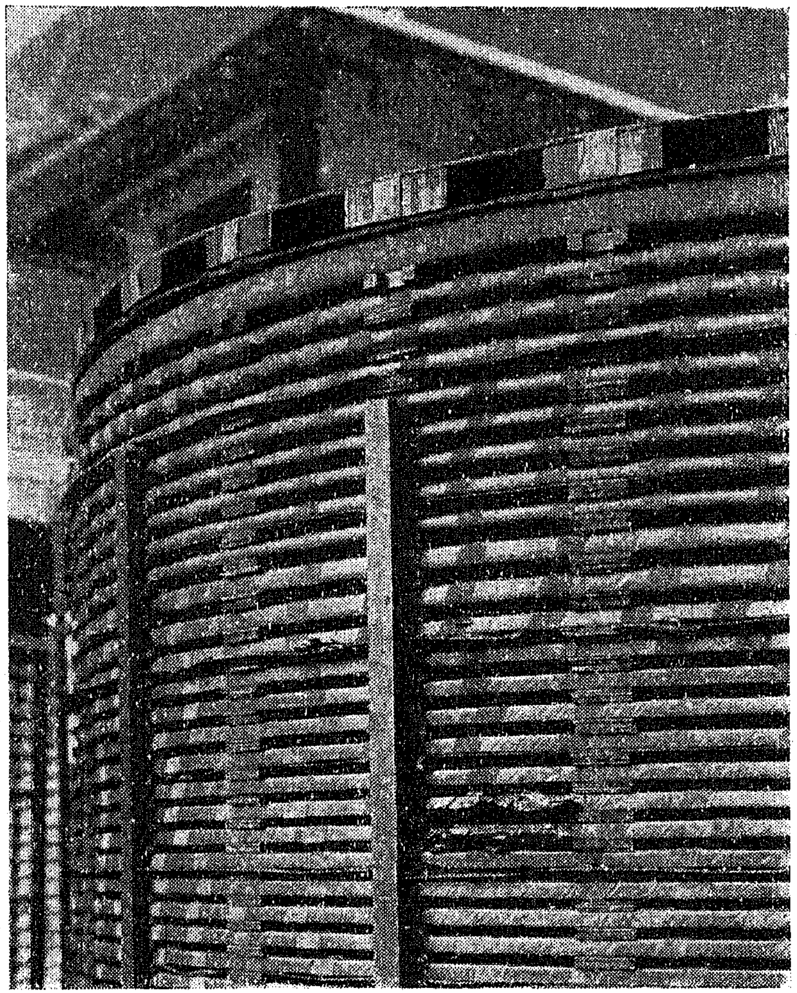

Fig. O.—Between-coil breakdown in a region below the line-end reinforcement of a large transformer winding, due to lightning.

paper by Dr. Allibone and Messrs. McKenzie and Perry. Our reply here is covered by the contribution to the discussion which one of us (J. L. M.)* made on that paper. Mr. Hansell also refers to the effect of resistance in the earth connections of a surge absorber. The remarks addressed to Dr. Allibone and Mr. Savage cover this point.

Finally, Mr. Hansell raises a particularly interesting point in connection with Figs. 29 and 30(*a*). The apparent anomalous behaviour of the circuit could be explained immediately if the current through the gap "g_1" persisted only for a very short period of time. This would correspond, in practice, to a lightning stroke with a very short tail. As Mr. Hansell points out—and in the paper we have subscribed to this view—such tails are long and in designing and operating our "direct stroke" circuits we were always careful to ensure that the generator had a surge-impedance characteristic and that the *current output persisted for very many microseconds*. This is exemplified in Fig. P, which shows the current through the gap "g_1," and it is seen that there is no question of the main arc having gone out during the period of time up to the appearance of the first negative loop in Fig. 30(*a*). Thus the fact that the voltage in Fig. 30(*a*) is almost zero after about the first half-microsecond must be due to the low value of the resistance of the arc in "g_1,"† and therefore at first sight the return opposite-polarity voltage reflection to the left from "g_2" should not appear across C_e at all. Its appearance, however, is due to the inductance of the circuit containing "g_1," which of necessity included rather long wires, and which prevented sudden changes in arc current.

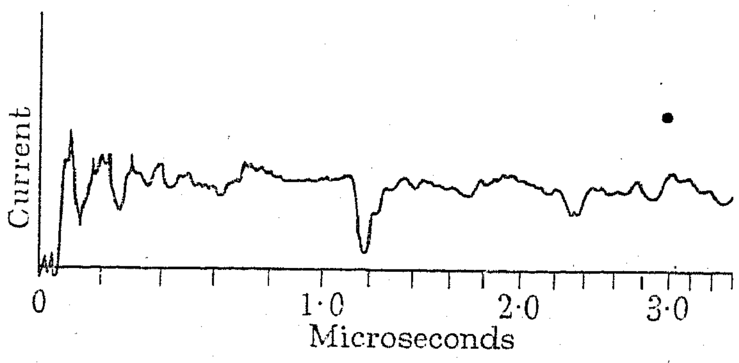

Fig. P.—Current through the gap " g," of Fig. 29(*b*) of the paper.

To illustrate the point, Fig. Q(*a*) shows the voltage across the transformer when all gap connections were kept as short as possible—in fact, short enough to be difficult of attainment in practice—and it is seen that there is little negative loop. When the circuit containing "g_1" was lengthened so that the connections were about 10–12 ft. long, the rest of the circuit remaining unaltered, the amplitude of the loop was considerable and similar to that shown in the paper. This is illustrated in Fig. Q(*b*), while Fig. Q(*c*) shows the effect of somewhat shorter gap connections of about 5 ft. In view of the fact that the lengths of connections used must be similar to those found in practice—no doubt in many cases they would be considerably longer—we are convinced that the voltages shown in Fig. 30(*a*) of the paper are truly representative of practice. Further, one can conclude that the lengths of connecting leads will have an important bearing in practice on the phenomena arising from direct strokes.

We have endeavoured to compress a complicated explanation into a few words, and we trust that we have given Mr. Hansell the information he requires. In any case we are indebted to him for raising such an interesting point.

In reply to Mr. Fennell we would say that the cost of obtaining protection, if it is only occasionally wanted on account of a minimum of lightning trouble, is certainly not justified. He is in error, however, in assuming that a surge absorber costs as much as a transformer. It is considerably less and varies, as we have stated, from 7 to 30 % of the transformer cost. Regarding his criticism that the surge absorber adds to obstructions, so preventing easy access to pole-mounted transformers, we would remind him of the fact that surge absorbers can be mounted in the terminal pockets of transformers, with, of course, a decrease in first cost and installation charges. Actually 90 per cent of the surge absorbers manufactured and sold in Canada are mounted in this way.

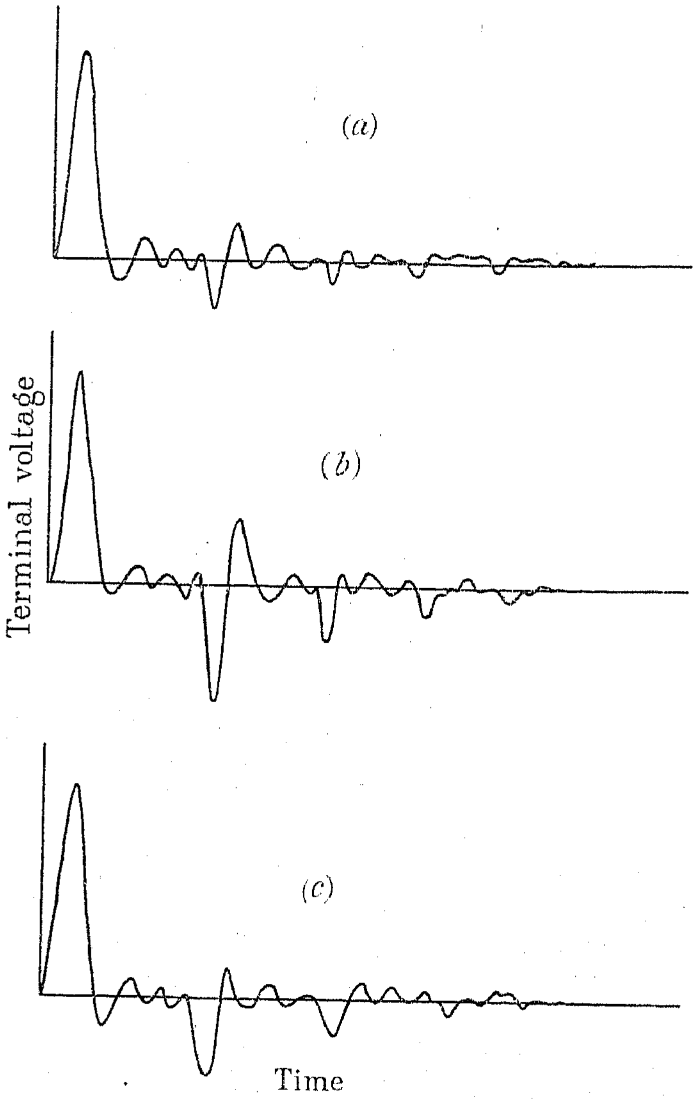

Fig. Q.—Terminal voltages corresponding to the direct-stroke conditions as given in Fig. 29(*b*) of the paper, with various lengths of connections in the circuit containing " g."

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* *Journal I.E.E.*, 1937, vol. 80, p. 163.

† Incidentally, oscillograms showed that the current in "g_2" did essentially cease after a short time and that the voltage wave sent along the infinite line to the right in Fig. 29 was a simple, short, chopped one.

METER AND INSTRUMENT SECTION: CHAIRMAN'S ADDRESS

By CAPTAIN B. S. COHEN, O.B.E., Member.*

"PROTECTIVE DEVICES FOR TELECOMMUNICATION PURPOSES"

(*Address delivered 4th November*, 1938.)

In looking for a suitable subject for an Address to this Section it was necessary to choose between measuring instruments specifically designed for telecommunication purposes and protective devices used in telecommunication, both subjects coming under the aegis of the Section.

As some of the special measuring instruments have already formed the subject of specific papers (including two during the past Session) I thought it advisable to take protective devices used in Telecommunication as the subject of my Address, particularly as little has been published in this direction, and as some of the devices used for telecommunication protection may prove of definite value in other protective directions. I propose to exclude protective devices used for radio purposes, as very little is done in this direction and major installations can be regarded as virtually self-protecting.

INTRODUCTION

It will be useful to commence with a brief review of telecommunication protection requirements, followed by a short summary of the nature of the over-voltage phenomena against which protection is required and some information of the type of damage met with, and finally descriptions of the protective devices in general use or in development.

Telecommunication circuits may consist of bare wires strung on insulators (open wires) and terminated at either end by leading-in cables or insulated wires. There are also circuits consisting entirely of underground or aerial cable conductors and others consisting of mixtures of open wire and cable conductors. These various types of circuits and the apparatus terminating them require protection from lightning discharge and from direct contact with, or inductive surges generated by, power circuits or any other extraneous sources of over-voltage.

In the case of telephone circuits the major requirements are protective devices at the subscriber's end of the line to protect him and his instrument; and devices at the exchange end to protect the staff and apparatus. Other devices may be required at intermediate points to minimize effects of surges on the line plant or to localize their effects to open-wire plant.

HISTORICAL

The need for protection of telecommunication plant from lightning arose immediately the first telegraph circuits were run, and air-gap arresters were universally used in early days. These were air-gaps either between metal discs or between metal plates with serrated edges. Then followed more elaborate devices incorporating chokes, the introduction of which was due to that eminent pioneer Sir Oliver Lodge who designed lightning arresters to prevent discharges on open-wire telegraph circuits from finding their way into submarine cables and causing serious and costly damage. In the past very little experimental means has been available to check optimum characteristics of protective devices. In recent years, however, it has become possible to carry out investigations in the laboratory with the aid of high-voltage generators simulating the lightning discharge very closely. Much valuable work has been done during the last few years in the study of over-voltage discharges on power circuits and apparatus, both in the field and the laboratory, and a number of papers have been published in the *Journal.* I would mention particularly, in chronological order, papers by Norinder, Melsom, Allibone, and Goodlet.

It will be instructive to refer to some of the major differences between power and telephone circuits from the protective standpoint. In the case of power circuits a comparatively few devices are required to protect a large extent of network, and apparently the need for individual protection of installations has not, so far as I know, been serious enough to warrant any general use of protective devices. In the telephone case, however, each individual circuit requires its protective devices. The number required in Great Britain alone consequently runs into millions. Again, telephone cables have dry paper insulation and break down with about $2 \cdot 5$ kV. As the dielectric is air, there is negligible delay action so that the protective devices must be more sensitive and rapid in operation than those used for power-cable protection. Much new work is being done and remains to be done in determining the optimum characteristics of protective devices used in telecommunication and in reducing the maintenance troubles due to their installation.

CLASSES AND SUBDIVISIONS

Protective devices can be separated into the following classes and subdivisions:—

(A) *High-Voltage Arresters.*
  (1) Pole-earthing devices.
  (2) Chokes.
  (3) Spark-gaps in air.
  (4) Spark-gaps at reduced pressure in gases.

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* Post Office Engineering Department.

(B) *Fuses.*
  (1) Line fuses.
  (2) Delay-action fuses:—
    Heat coils.
    Thermally-loaded fuses.
  (3) Exchange fuses with alarm attachments.

(C) Acoustic shock-absorbers: voltage limiters.

LIGHTNING DISCHARGES

A brief résumé of the latest information with regard to the nature of the lightning discharge will first be useful.

Since Sir George Simpson's Kelvin lecture on lightning, in 1929,[*] further information has been obtained with the aid of Boys's high-speed camera, which, in the hands of Schonland, Malan, and Collens in South Africa[†] and others elsewhere, has given most valuable information. Prof. B. L. Goodlet, in his paper on "Lightning,"[‡] has dealt fully with the physical phenomena and also the effect of lightning strokes on overhead transmission lines, whilst Dr. Allibone has shown[§] the relationship between the laboratory-created long spark and the lightning discharge.

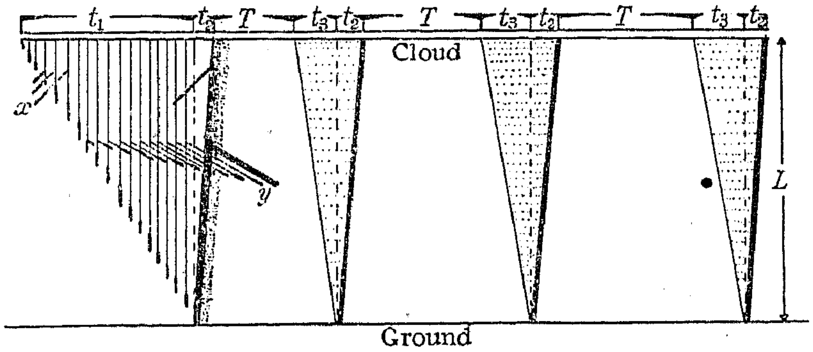

Fig. 1.—Formation of a lightning flash.
Average values: $t_1 = 0\cdot01$ sec.; $t_2 = 0\cdot00004$ sec.; $t_3 = 0\cdot001$ sec.; $T = 0\cdot03$ sec.; $L = 2\cdot0$ km.

Schonland has photographed a considerable number of discharges between clouds and earth, and these primarily concern the engineer. Fig. 1 (from Schonland's 1935 paper) illustrates the formation of a lightning flash.

Each lightning flash to earth recorded by him consists of a series of anything from 1 to 27 separate strokes varying in time of separation from 0·6 millisec. to over 0·5 sec. The first stroke is different from the remainder, being in general considerably more intense and always much more branched.

Each stroke consists of two components. First there is a comparatively slow progressive discharge from cloud to earth which produces an ionization path. This is termed the leader and may take as long as 0·01 sec. to complete. When complete there is a very rapid return flash from the earth back to the cloud which has a duration of the order of 50 microsec. and may be termed the main flash. The leader to the first stroke has been referred to by Schonland as "stepped," as the discharge progresses in steps of about 50 metres with pauses of the order of 100 microsec. between successive steps. Many downward branches occur in the first leader stroke, and the first main stroke takes place along these branches as well as along the successive steps of the leader. The leaders of the subsequent strokes are rarely stepped or branched but usually consist of a single dart following the path of the first leader. From the standpoint of development of protective devices the engineer may regard the lightning stroke as in general a discharge from a cloud with an average duration of the order of 50 microsec. A typical rate of voltage-rise for surges induced in lines is 1 000 kV per microsec., although much higher rates have been recorded.

Experiments carried out about 30 years ago using a Wimshurst machine and an exposed but undeveloped photographic plate provide an interesting resemblance to the phenomenon of leader flash, although the analogy is probably a somewhat remote one. I have recently resuscitated the old experiment and modified the technique and propose to demonstrate it.

As a source of high potential I shall use a 50 000-volt transformer with the output voltage rectified. The discharges will take place between a cathode representing a negatively charged cloud face and an earthed anode over the surface of a sheet of thin bakelite coated with a layer of gelatine impregnated with silver iodide and titanium oxide. It will be seen that the discharges, whilst somewhat of the nature of Lichtenberg figures, consist of carbonized gelatine following ionization paths; they develop from both electrodes, but generally start from the negative electrode, and ultimately meet.

A line drawing traced from a typical discharge is shown in Fig. 2. It will be observed that the positive and negative tracks are different. In addition the positive track is surrounded by a nebulous dark margin which could not be illustrated in the line drawing and of which there is no trace on the negative track. Independent discharges sometimes manifest themselves in the area between the electrodes, as illustrated also by Dr. Allibone in some of his photographs.[*] The ionization process in the gelatinous medium has a time-lag of the order of 10^6 compared with gaseous discharges. The former therefore meander along quite slowly; they are accompanied by a sort of wave-front of very vivid balls of white fire. Dr. Allibone tells me that he has found the results of similar discharges on the interior of high-voltage insulator bushings, but has not seen them in course of production. I have not previously published particulars of these experiments.

Having briefly dealt with the nature of the discharges, we have still to get some idea of the character of the damage to telecommunication plant before proceeding to describe and discuss protective devices.

The series of thunderstorms of unprecedented intensity for this country which occurred during this summer, mainly in the south-west and west of England, whilst unfortunately doing an exceptional amount of damage, have at the same time produced some interesting and instructive phenomena. Open-wire telephone lines were fused in a considerable number of localities and it was possible to inspect some of the damage *in situ*.

In the majority of cases line wires of copper, cadmium copper, or bronze, weighing from 40 lb. to 100 lb. per mile (very exceptionally), i.e. 50 mils to 79 mils in diameter, were fused at a single point and often with only a few inches near the break softened. But occasionally both 40-lb. and 70-lb. line wires have been evidently subjected to an intense heat over an entire span or series of spans. The wire in these cases becomes completely annealed. On a basis of a 50-microsec. discharge the current necessary to raise the whole cross-section of a 70-lb. bronze wire to incandescence would be of the order of 100 000 amp.

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[*] *Journal I.E.E.*, 1929, vol. 67, p. 1269.

[†] *Transactions of the South African I.E.E.*, 1937, vol. 28, pp. 204 and 214; also *Proceedings of the Royal Society*, A, 1934, vol. 143, p. 654, and 1935, vol. 152, p. 595.

[‡] *Journal I.E.E.*, 1937, vol. 81, p. 1.

[§] *Ibid.*, 1938, vol. 82, p. 153.

[*] *Loc. cit.*

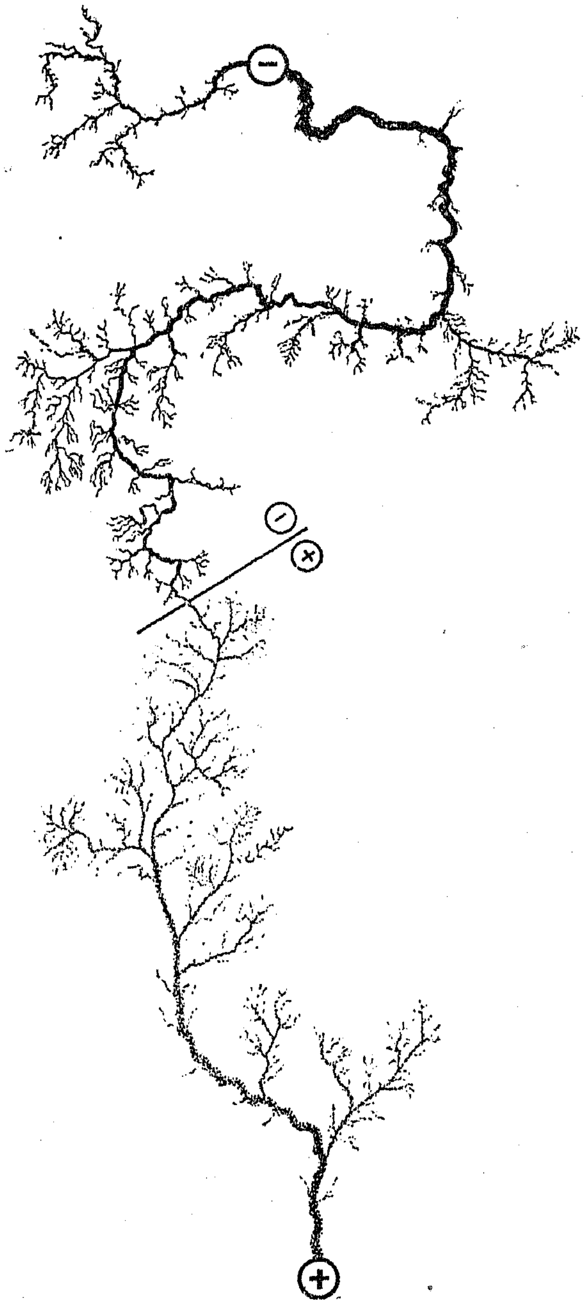

Fig. 2.—Typical discharge through gelatinous film on bakelite sheet.

Amongst the cases of fused line-wire examined, there are a number of particular interest in which the wires have been fused on the surface in small oval patches and the fused metal appears to be drawn into filaments, the tops of which have welded into a projecting smooth nodule.

The projecting nodules generally lie in one plane and are always displaced in the same direction towards the ends of the fused oval patches (see Fig. 3).

Similar nodular fusings are met with in arc discharges. The interaction between the magnetic field round the conductor and that at right angles round the arc give rise to a translatory motion.

A most remarkable case of fusing occurred at Rocester, near Stoke, where both wires of 15 successive spans involving over $\frac{1}{2}$ mile of 40-lb. cadmium copper and normally 12 in. apart were neatly welded together (see Fig. 4). The longest continuously welded lengths were of the order of 30 ft., and in addition there were a very large number of short pieces fused at both ends or fractured at both ends under conditions of high temperature. An onlooker stated that a sheet of flame ran along the wires, which fell white-hot into a hedge.

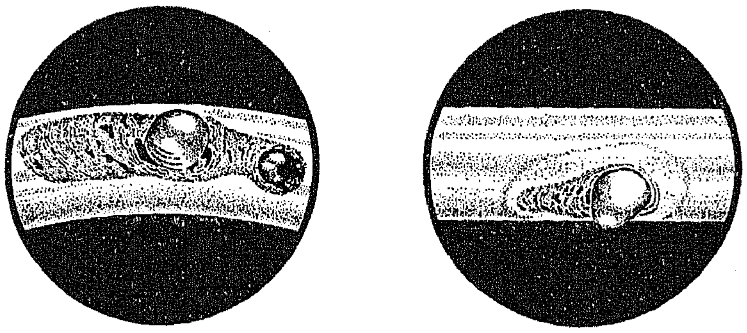

Fig. 3.—Examples of nodular fusing caused by lightning.

No other exactly similar cases have been recorded in this country, but it is of interest to note that a similar phenomenon occurred with 70-lb. bronze wires in Tenterfield, New South Wales, in 1933, when the wires were welded together over 13 pole spans approximately 50 yards in length. I find on inquiry that no cases of this nature have been recorded in the United States, in spite of the very large amount of open wire existing there.

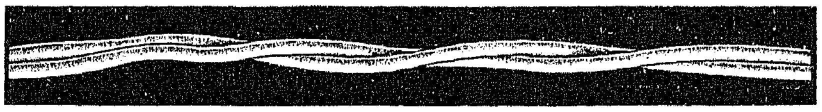

Fig. 4.—Pair of wires welded together by lightning discharge.

The most likely explanation of this effect appears to be that the discharge took place over the two wires in the same direction, which would result in a strong attracting magnetic field between them. With a steep-fronted discharge along two wires, comparatively close together, the current would tend to flow along a portion only of the adjacent faces of the wires (proximity effect) and might fuse this portion of the wire only. At the same time the powerful attraction (electro-striction) would draw the wires together. This theory has just received ample confirmation from an experiment by Dr. Allibone, who has actually simulated the effect with two wires of tinned copper, No. 37 S.W.G., spaced about $\frac{1}{4}$ in. apart and subjected to discharge in parallel, using an impulse generator. The wires were attracted to each other and welded, and he has kindly sent me the sample which is exhibited here. He points out quite rightly that the multiple character of the normal flash, which may make it last for about 0·5 sec., would give the wires ample time to be attracted into contact and then welded. I am very much indebted to Dr. Allibone for his interest in this matter. Somewhat similar electro-strictive effects have been recorded with vulcanized-rubber-insulated pairs when the conductors have been forced through the insulation into contact with each other. Mr. Spilsbury has kindly sent me a sample of wire from one such case which occurred at Aldershot in 1931.*

RECURRENT PHENOMENA

The most recent definite evidence of a recurrent effect, such as a series of peak-current points, occurred 2 years ago near Haywards Heath, where a length of 40-lb. bronze wire was fused at about 12-in. intervals, the fused lengths having been found on the ground just below the span. Complete explanations of this and the other phenomena previously mentioned are still to be formulated, and research workers with impulse generators giving sufficient energy might find this a worthy subject for further investigation.

Many other interesting cases of lightning damage to telephone plant have been recorded; I shall show a few lantern slides of recent damage, but time will not permit me to deal with them in any detail.

From a study of these and other cases there is very little doubt that the damage generally results from direct discharges on to the lines and not from induced surges. This is also the conclusion arrived at by Peters and Schulz, who wrote a very comprehensive paper on telecommunication plant protection in the German Post Office.† They estimated that between 70 and 80 % of damage was due to direct discharges.

PROTECTIVE DEVICES

I shall now briefly describe the various protective devices in general use.

(A) HIGH-VOLTAGE ARRESTERS

(1) Pole-Earthing Devices

At an early period it was customary to provide each pole of an open-wire circuit with a lightning conductor. At the present day, whilst every distribution pole is earthed, only every tenth pole on certain types of route is so treated and it has been assumed that a considerable measure of protection is afforded to the 5 poles on each side of the earthed pole. It is difficult, however, to obtain any very definite data to substantiate this, though an occasional earthed pole may localize the damage in the event of a direct hit. However, in exposed positions subject to lightning storms it is the practice to earth every pole. The earthing wire consists of a 150-lb. hard-drawn copper wire run down the pole on the opposite side to the cross-arm, and wound into a flat spiral at the butt of the pole (see Fig. 5). In the case of distribution poles where a lead-sheathed underground cable is extended up the pole to connect to the open wires running to the various subscribers, the cable sheath is likely to be a much better earth than the lightning-conductor earth, and hence it has been found desirable to bond the earth wire to the lead sheath of the cable at a high point on the pole to obviate the danger of side flashes from wire to sheath.

In order to demonstrate some of the lightning discharge effects I shall make use of an impulse generator. The first demonstration shows the shielding effect of an earthed pole associated with several unearthed poles even when the former is out of the direct line of discharge. The second demonstration shows the bad effect of a pole earth of higher resistance than the lead sheath to earth of a leading-in cable on the same pole, and also the desirability of bonding cable sheath and earth wire.

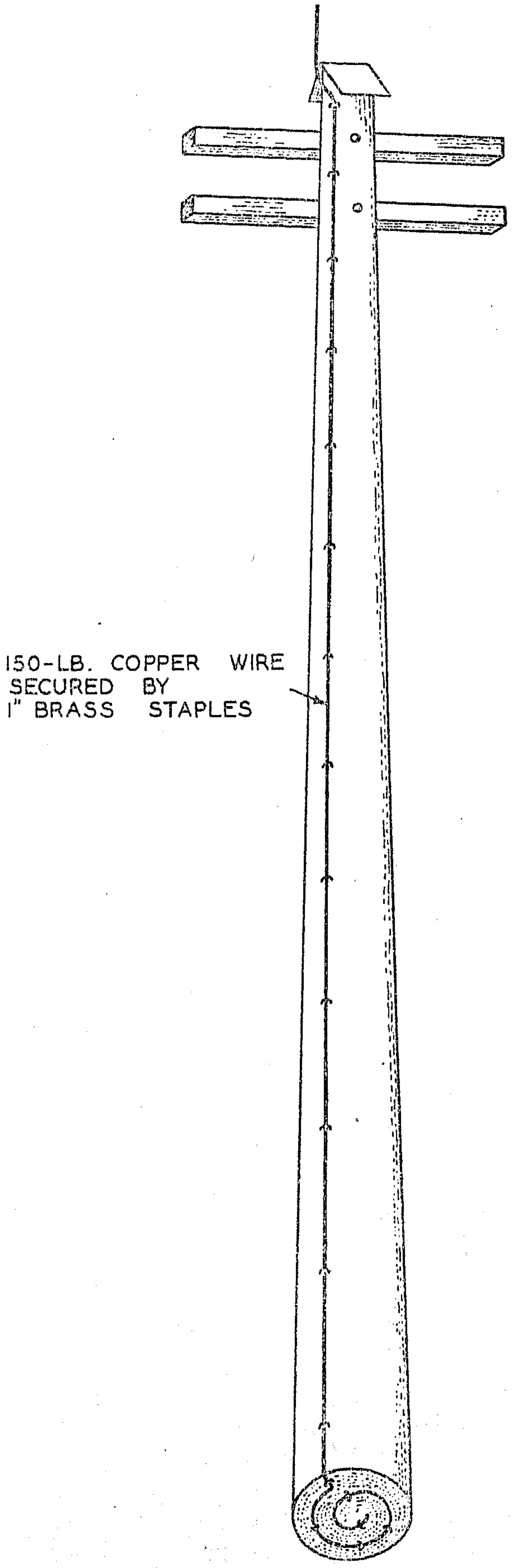

Fig. 5.—Earth on pole lightning conductor.

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* See *Nature*, 1931, vol. 128, p. 872.

† *Elektrotechnische Zeitschrift*, 1937, vol. 58, p. 1129.

(2) Air-Gap and Choke Protector

A choke and air-gap protector has been used for very many years to protect submarine and river-crossing cables when connected to open wires. The choke consists of 18 turns of 35 mils diameter (20 lb.) rubber-insulated wire and is used in combination with air-gap dischargers and fuses. A modernized version of this device is under consideration and such a device may offer advantages for use in those cases where the plant is not under continuous supervision, e.g. small unattended automatic exchanges, as a comparatively wide spark-gap could be used which would not be liable to short-circuit after carrying a discharge, and it also offers possibilities of localizing damage to open wires if fitted at the junction between open wires and cables.

At one time it was the practice to safeguard the cables from damage by fitting a fuse sometimes associated with a spark-gap at the connecting point to open wires. This has been abandoned in this country owing to maintenance troubles, although the practice is followed in countries where heavy storms are common, such as the United States and South Africa. The choke and spark-gap combination may, however, give less trouble in maintenance than fuses and small spark-gaps, and its use may reduce liability to cable damage. Here is an experimental form of choke to connect into open wires at the point where they are connected to a cable. This is incorporated in the insulator itself (see Fig. 6).

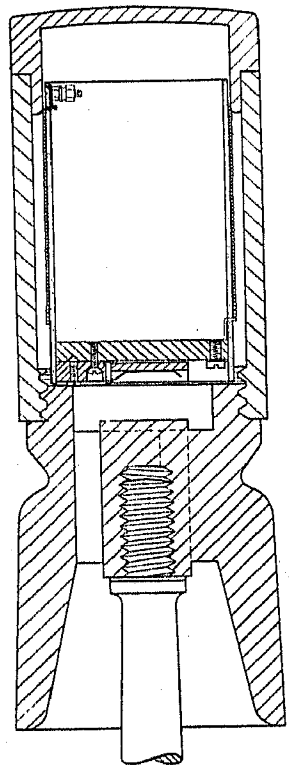


Fig. 6.—Experimental choke coil and spark-gap, mounted on a standard insulator.

(3) Spark-Gaps in Air

The type of high-voltage arrester at present in use on Post Office lines at exchanges and subscribers' premises consists of a spark-gap in air, two small carbon blocks forming the electrodes. In earlier types the carbon blocks were separated by mica slips about 4 mils thick, having three small holes $\frac{1}{8}$ in. diameter. These arresters sometimes developed low insulation resistance, owing to the ingress of damp and also to dust either from external sources or from disintegration of the carbon blocks. To reduce the liability to this fault, the mica was replaced by a double layer of varnish on each carbon block. The operating voltage of this type is 500–750 volts, and the discharge takes place through the varnish film (see Fig. 7). Once the film is punctured by a discharge, however, carbon dust tends to percolate through and earth the line. Other methods of overcoming the dust and damp trouble have been tried. For example, in America one carbon block is replaced by a porcelain block containing a small carbon insert sealed into a central recess with fusible glass. Any carbon dust that is formed tends to fall into the recess instead of remaining between the blocks. In a Swedish type of arrester the ingress of external dust and damp is prevented by cementing together the two carbon blocks and mica separator by a cellulose lacquer.

With the object of producing an arrester which is free from the damp and dust trouble, and which will withstand a number of discharges without developing a short-circuit or suffering appreciable change in operating voltage, work is now proceeding on the development of a type having metal electrodes completely enclosed in an insulating moulding.

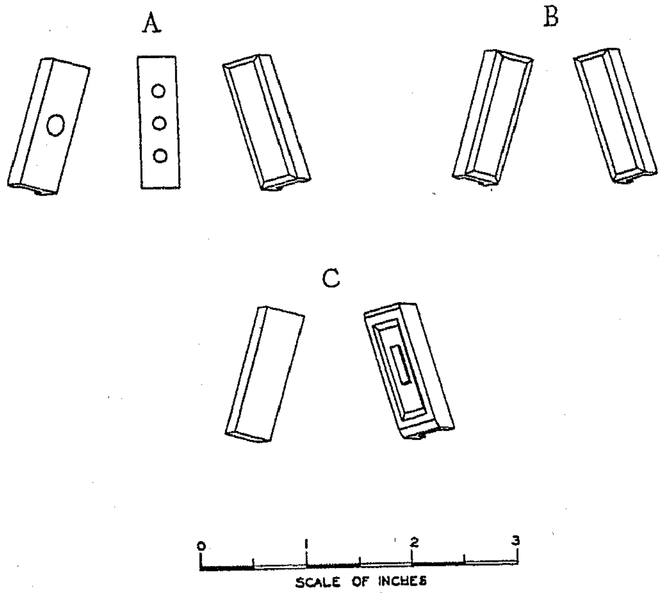
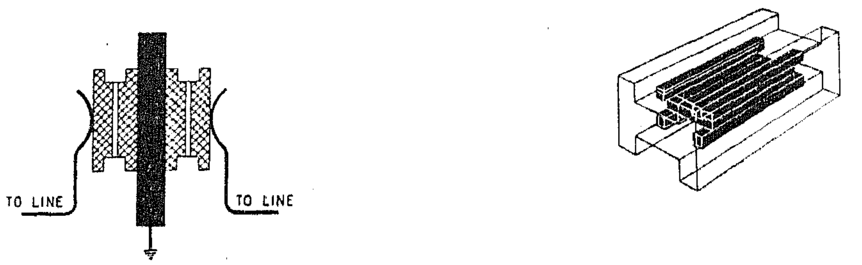


Fig. 7.—Carbon arresters.

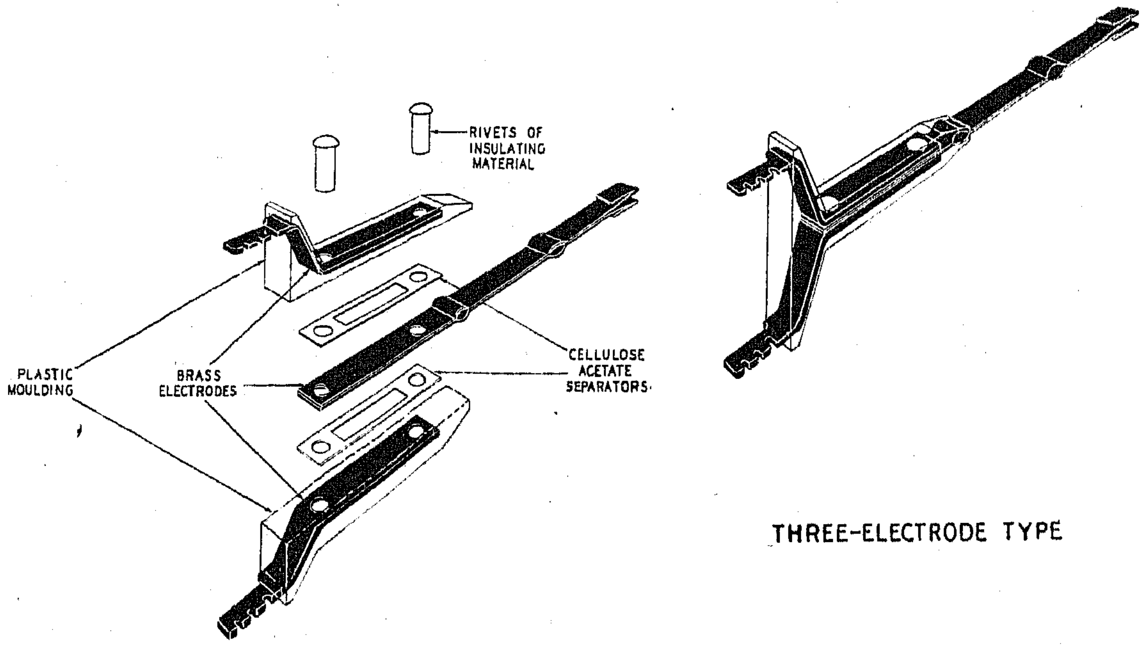
A. Early form with mica separator and fusible plug.
B. Present varnished-carbon type.
C. American-type carbon insert in porcelain holder.

The electrodes may be of stainless steel or brass and are enclosed in an insulating moulding material such as mipolam. They are separated by a spacer of cellulose-acetate film with a window in it. A spacer of about 4 mils thickness will have an operating voltage of 750 ± 150 volts. Discharges are liable to produce craters with raised margins on the surface of the electrodes, and in order to ensure that these craters do not result in contacts a separation of the order of 4 mils is found to be advisable.

The 2-electrode form has been developed for use at subscribers' terminations or in existing types of exchange arrester mounting, whilst the 3-electrode form with central earthing electrode has been developed for use in a special form of mounting which will be referred to



TWO-ELECTRODE TYPE



THREE-ELECTRODE TYPE

Fig. 8.—Moulded-type arresters.

later. Fig. 8 is a diagrammatic representation of these spark-gap protectors.

(4) Spark-Gaps at Reduced Pressure (Discharge Tubes)

These consist usually of either 2 or 3 electrodes sealed into a glass tube containing a gas at reduced pressure, usually neon, sometimes with a trace of argon. They are more bulky and expensive than air-gaps but have the advantage of being sealed against dust and damp, and can be constructed for a lower breakdown voltage. Breakdown voltages of between 100 and 500 volts are readily obtainable. Moreover, the spacing of the electrodes is much greater, so that the danger from short-circuiting is practically non-existent. On the other hand, under very heavy discharge the glass container may be punctured and the arrester then becomes an air-gap with a very large gap and consequently a very high breakdown voltage. For this reason they are considered less suitable than air-gaps for protection against lightning. They are, however, very suitable for the protection of lines against high voltages induced from power circuits under fault conditions. In this case it is possible to calculate fairly accurately the maximum current the tube will be required to carry, and to install a tube capable of carrying this discharge for the duration of a fault, without damage. Gas discharge tubes have been installed, with this object, in Northern Ireland where the induced voltage under power-circuit fault conditions may reach 1 400 volts in some of the open-wire telephone circuits. Tubes are installed at the beginning and end of the section of line exposed to the liability of induced high voltage. The 3-electrode type is used, one electrode being connected to each line and the third to earth.

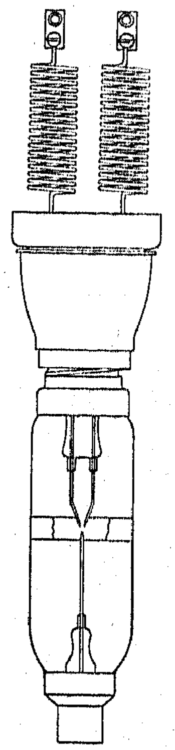


Fig. 9.—Three-electrode gas-filled arrester used for protection against surges induced from power systems.

Discharge tubes used to protect lines from high-voltage inductions are, of course, also subject to operation by lightning discharges, and if such discharges puncture the tubes the line is no longer protected from high-voltage induction, no indication of this eventuality being given. In order to minimize this possibility, the discharge tubes have been provided with high-frequency chokes consisting of 15 turns of wire ($\frac{3}{4}$ in. diameter) and supplementary air-gap discharge points in series with each line electrode (see Fig. 9).

(B) FUSES

(1) Line Fuses

These are quick-acting fuses of low thermal capacity. Fig. 10 shows three types in use. The commonest type, fitted at the exchange end of subscribers' lines and sometimes also at the subscriber's end, consists of a phosphor-bronze wire totally enclosed in a narrow-bore porcelain tube fitted with metal end-caps. These fuses will carry 1·5 amp. continuously but will fuse with 3 amp. in 30 seconds and will rupture with 1 000 amp. at 600 volts (d.c.) without maintaining an arc. They are connected between the spark-gap arrester and the line to be protected. Although primarily intended to protect against contact with power circuits they will also operate in the event of a very heavy lightning discharge, and may protect the arrester from permanent damage. It has been proposed to increase the rating current to 2·5 amp. and the operating current to 5 amp. in 30 seconds.

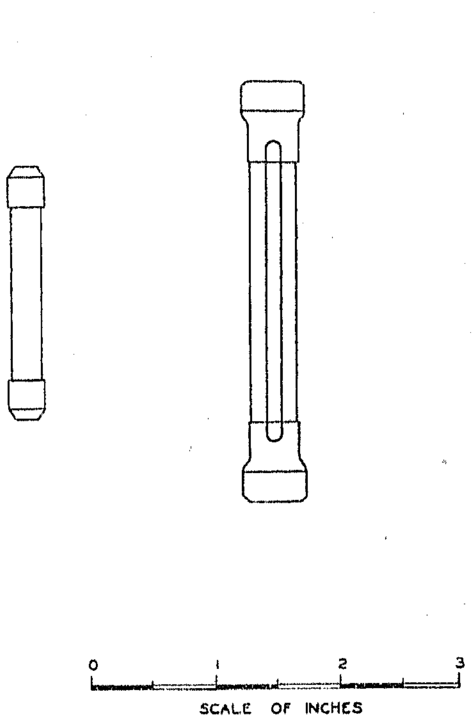


Fig. 10.—Types of line fuse.

(2) Delay-action Fuses

Although terminal apparatus is protected by the line fuse against undesired currents exceeding 3 amp., it is possible that damage from overheating may result from smaller currents if these are sustained for several minutes. On the other hand, if the line fuse is designed to operate at a lower current it may be operated by surges which occur in the normal working of the circuit. To overcome this difficulty, fuses having delayed action are used. These are of two types, the heat-coil and the spiral fuse.

(1) Heat-coil type.—This type consists essentially of a small bobbin carrying a winding which is connected in series with the line to be protected. A brass pin passes through the centre of the bobbin, and is held in position by means of a fusible metal insert. A sustained fault current raises the temperature of the bobbin and consequently of the pin and fusible metal, and eventually the

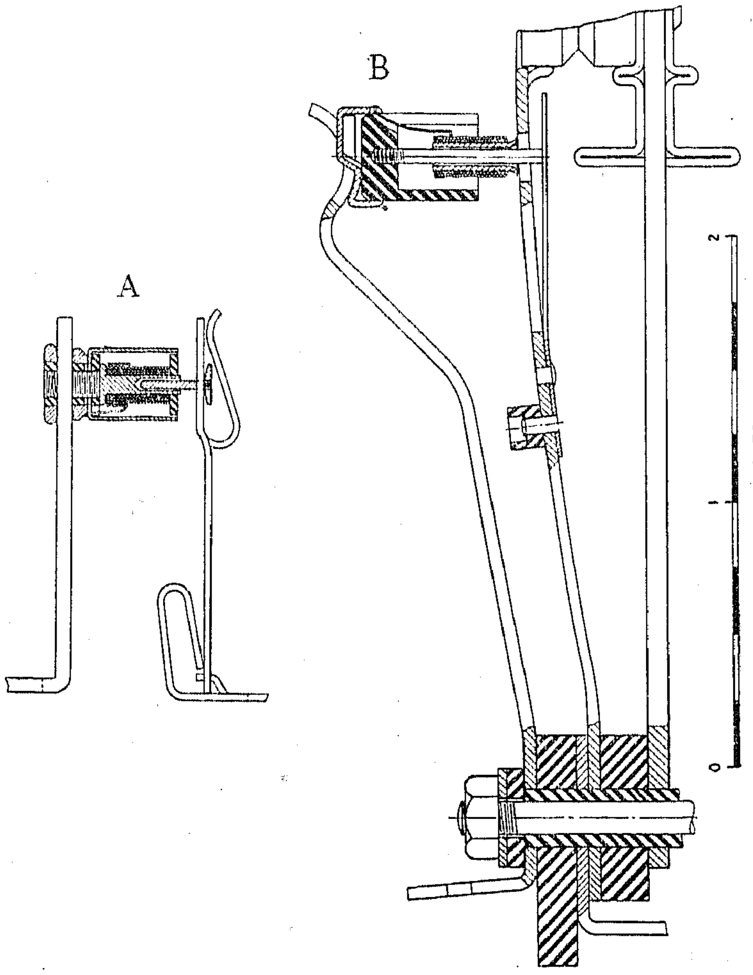


Fig. 11.—Heat coils.

A.—Break type.
B.—Earthing type.

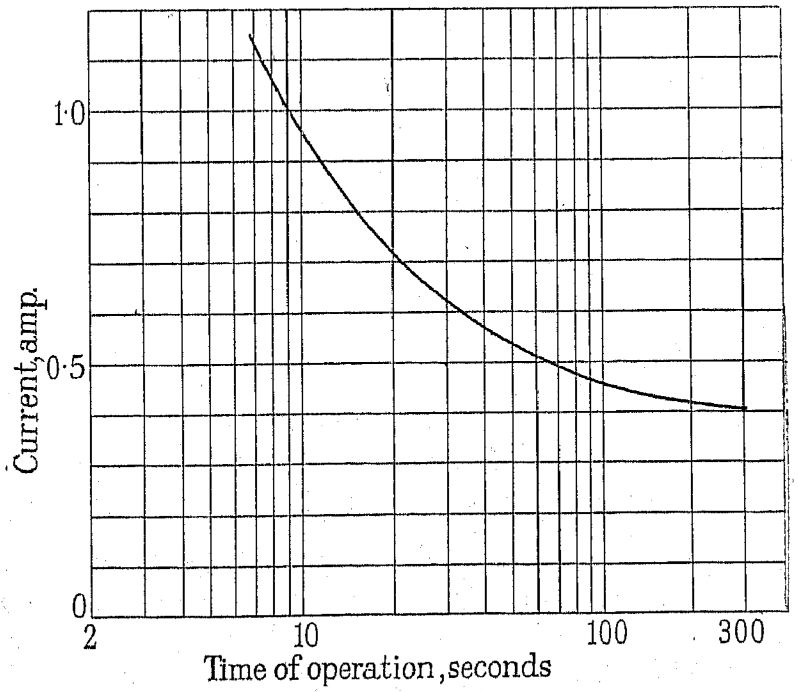


Fig. 12.—Heat-coil characteristics.

latter melts. Under the action of a spring the pin moves relative to the bobbin, and the line is either disconnected or earthed, depending on the type of heat coil. Section drawings of both types are shown in Fig. 11. A typical characteristic showing the operating time for various values of current is shown in Fig. 12.

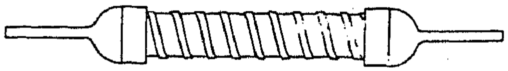


Fig. 13.—Spiral-type thermal-delay fuse.

(2) **Spiral-fuse type.**—This type of fuse, which is still experimental, is intended to replace the heat coil, and its characteristics are very similar. In its present form it consists of a helix of tinfoil strip wound on a soda-glass rod (see Fig. 13). The fusing of the strip is delayed by the heat capacity of the glass rod. The actual delay characteristic depends on the material of the rod and the thickness and spacing of the foil. The curves in Fig. 14 show the effect of different rod materials.

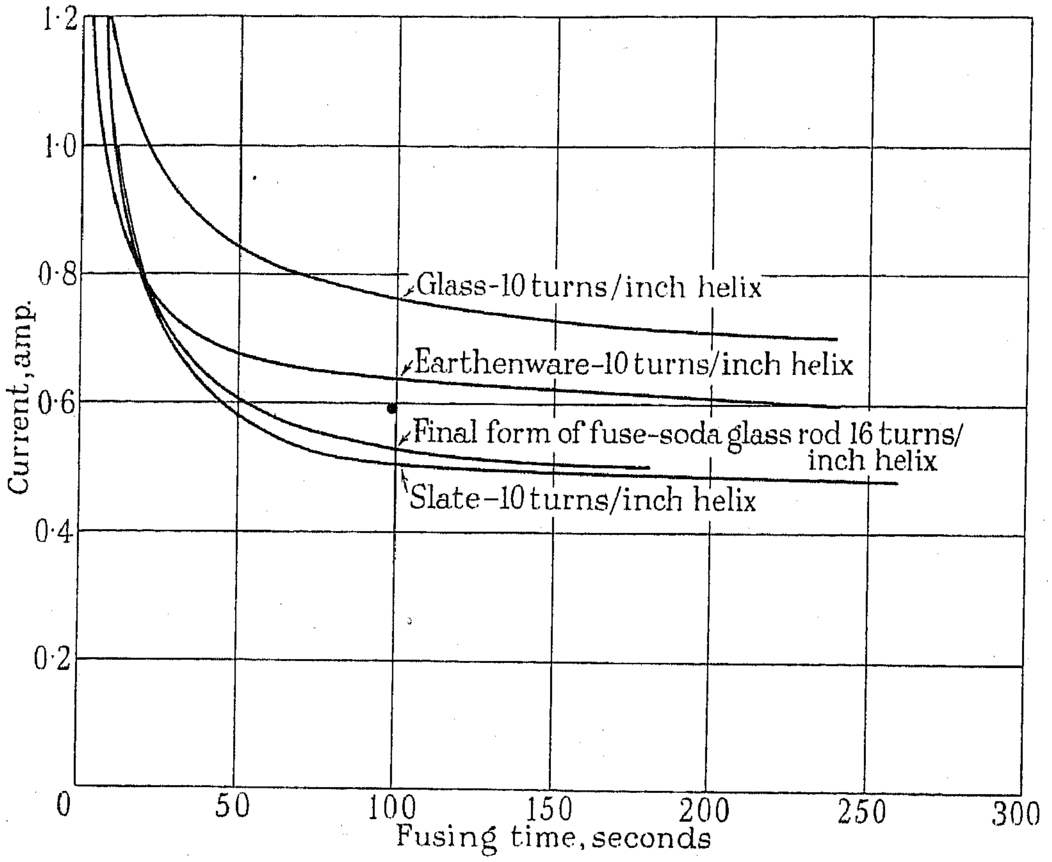


Fig. 14.—Effect of supporting rod material on thermal-delay fuse characteristics.

It is expected that this type of delay-action fuse may prove more reliable in practice than the heat-coil type, which is liable to occasional false operation owing to mechanical failure or "cold-flow" of the fusible metal.

Complete Exchange Protection Unit

The present-day practice in this country is to provide line fuses at the exchange on the external side of the main distributing frame, and heat coils and carbon-electrode arresters on the internal side.

Practice in the near future may substitute brass-electrode arresters and thermal-delay fuses of the types already described, in place of the carbon electrodes and heat coils, or alternatively an entirely new assembly with the new protective devices concentrated in a small plug-in unit may be adopted. Fig. 15 shows an experimental type.

Subscriber's Protector

The existing type of protector in general use contains a line fuse, a heat coil, and a pair of carbon protector blocks for each line. These are held by clips mounted on a small base and provided with a rectangular moulded dust cover (see Fig. 16). In cases where there is no liability to contact with power circuits, the line fuses and heat coils are replaced by dummies.

In the near future the possibility of replacing fuses and heat coils by thermal-delay fuses, and carbon electrodes by brass ones, is under investigation.

When the subscriber's protector is subjected to heavy discharges, the composition covers are frequently shtatered. This is no doubt due to the high air pressures generated by the discharges. A simple safeguard would be the provision of a small window which could be covered with some thin material to exclude dust.

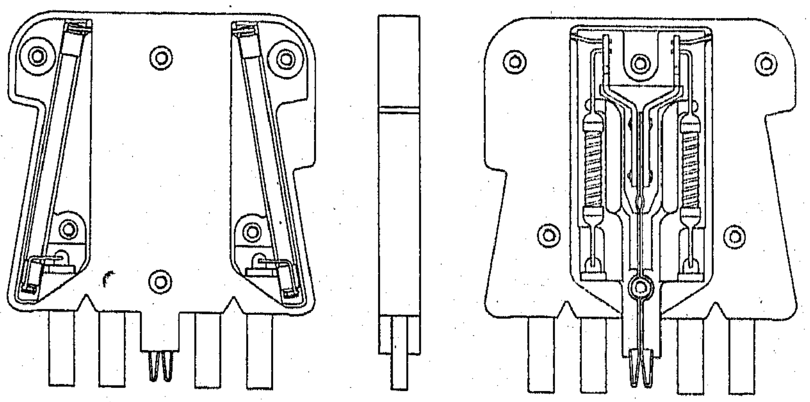


Fig. 15.—Plug-in type protector-unit.

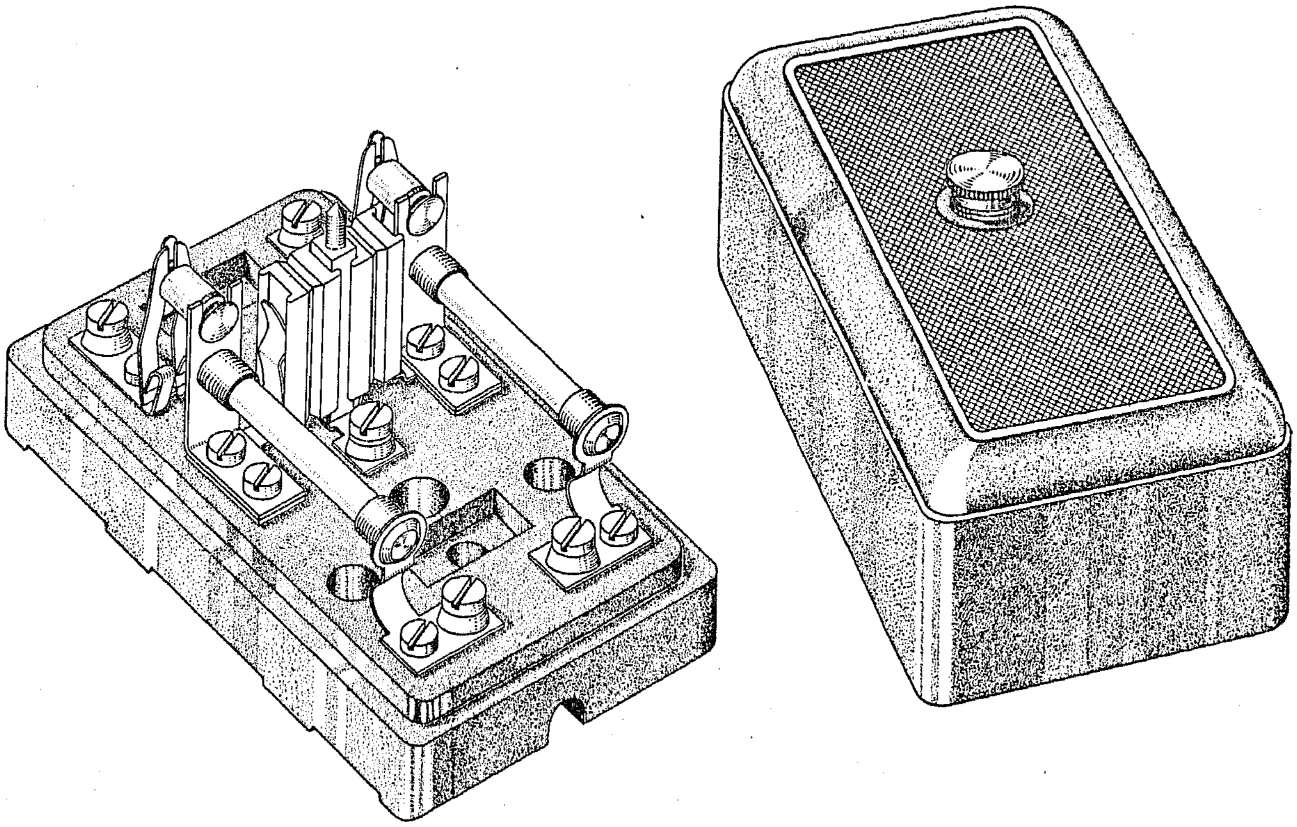


Fig. 16.—Subscriber's protector unit.

Protection Afforded by Cable Conductors in cases where Circuits consist partly of Open Wires and partly of Cable Conductors

It is the practice in many administrations to assume that the existence of any considerable length of cable in a circuit constitutes sufficient protection from over-voltage surges, and no arresters are fitted in such cases. It is of interest to consider briefly what protection is actually afforded.

Ordinary dry paper-insulated lead-sheathed cables will break down with an average maximum value of 2 500 volts. The application of a steep-fronted pulse such as a 250 000-volt surge from an impulse generator to the outer wires of various lengths of a typical subscriber's underground cables with open-circuit conditions, results in end voltages becoming approximately constant at values of the order of 600–800 volts when the cable length exceeds about 100 yards. Fig. 17 shows how the surge is reflected from the cable ends when they are open-circuited. When the cable ends are terminated on exchange apparatus the reflections are smoothed out. The end voltage is much the same as in the open-circuit condition.

From these results it can be anticipated that exchange apparatus terminating underground cable circuits is not likely to be subjected to surges exceeding 2 500 volts, and if a maximum length of 20 miles of cable is assumed the energy will not exceed 4 joules.

Whilst these values are unlikely to result in extensive fire damage, coil windings can be burnt out and protection is therefore advisable. In the United States it is the custom to fit a length of not less than 6 ft. of a special protective cable at the junction of open-wire and underground cable. This cable has conductors of 0·02 in dia. and breaks down with a voltage somewhat below that of the underground cable.

(3) Alarm Fuses

These are used in the telephone exchanges to protect the switching plant and internal wiring. The fusible element is a fine wire held in tension by a light spring (see Fig. 18). When the wire melts, the spring makes contact with a bar behind the fuse and closes a circuit which operates an alarm bell and also lights a lamp. For normal load currents up to 3 amp. the alarm fuse carries the whole of the current. Recently, however, the practice has been introduced of connecting an alarm fuse in parallel with a cartridge-type heavy-current fuse, in cases where an indication of the failure of the cartridge fuse is required. The alarm fuse operates immediately after the main fuse. It has been found that the arrange-

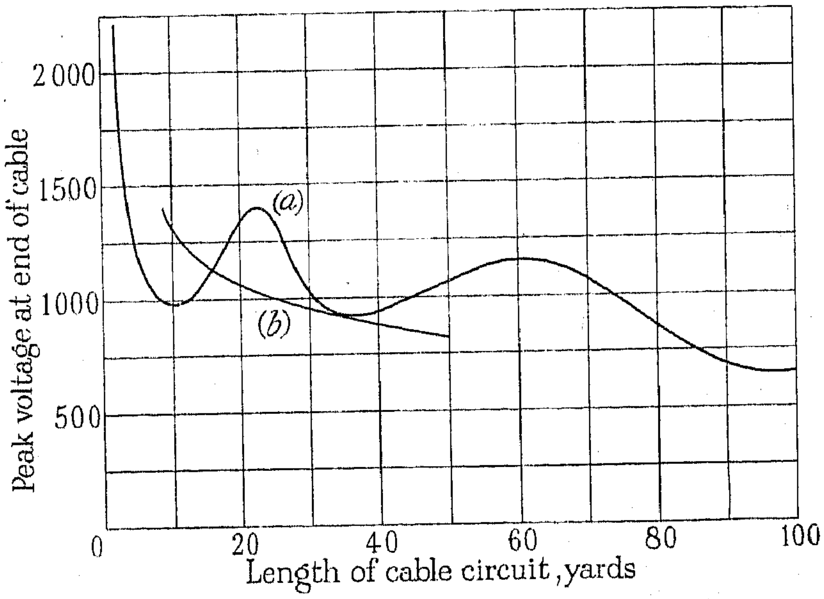


Fig. 17.—Surge-voltage protection of exchange apparatus by paper-core cable.

(*a*) Open-circuited cable.
(*b*) Cable terminated in exchange apparatus.

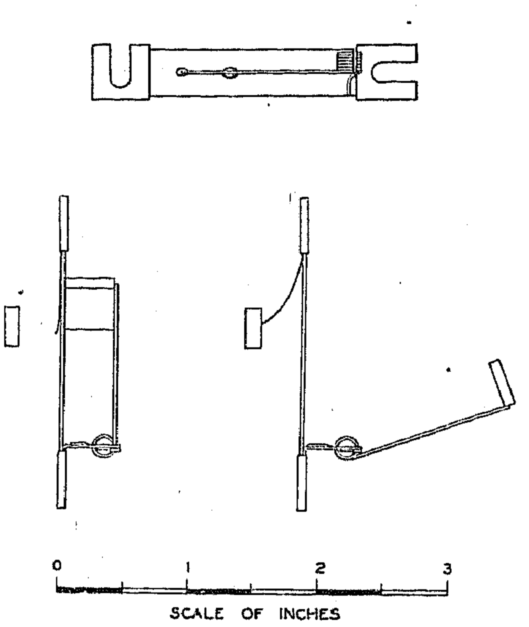


Fig. 18.—Alarm-type fuse.

ment is quite satisfactory, and even when the main fuse interrupts a current of some hundreds of amperes in an inductive circuit, so that there is a considerable rise of voltage across the alarm fuse after operation, no arc is formed and the fuse mounting is undamaged.

(C) ACOUSTIC SHOCK-ABSORBERS: VOLTAGE LIMITERS

This type of device is used either to protect the telephone user from the deafening effect of sudden voltage-rise in the circuits, giving rise to clicks, or to limit the voltage-rise at the peaks of high-volume speech which produce inarticulate sounds owing to the non-linearity of the telephone instruments or their associated amplifying devices. The cuprous-oxide rectifier is most generally used as an acoustic shock-absorber. Its rectifying property is only incidental, and usually two cuprous-oxide units are used connected in parallel in opposite directions to form the absorber, which is connected across the terminals of the receiver. When the voltage-rise is unduly high the resistance of the absorber drops and shunts the receiver. Fig. 19A shows one of these absorbers intended for mounting inside the receiver itself. Fig. 20 shows the voltage/resistance characteristic of a typical cuprous-oxide shock-absorber. The articulation of the receiver in general use at present is quite unaffected at normal speech levels, and is if anything slightly improved at somewhat higher levels owing to the removal of the deafening effects produced by the peaks. With abnormally high levels of speech, however, speech intelligibility is naturally reduced. The effects of the absorber on receivers which may be introduced into service in the near future have still to be determined. [Capt. Cohen here gave a demonstration of the protective action.]

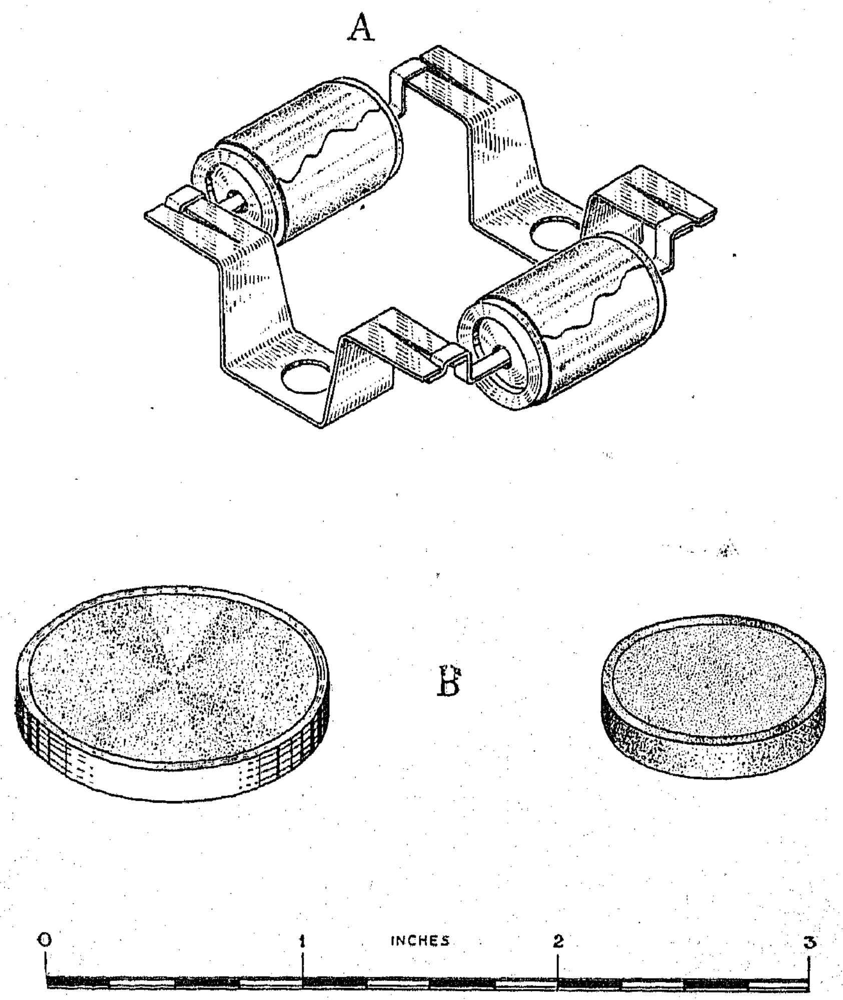


Fig. 19.—Acoustic shock-absorbers.

A.—Cuprous-oxide type.
B.—Typical varistor discs.

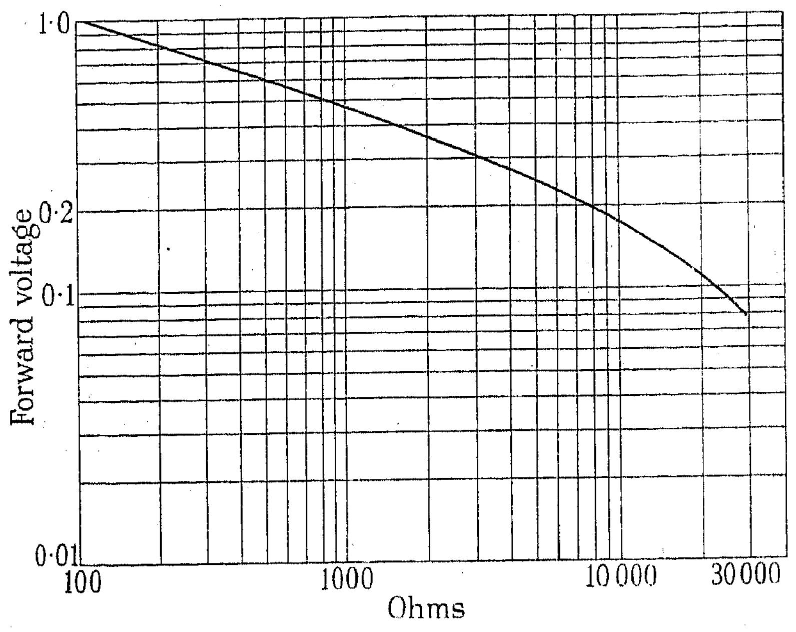


Fig. 20.—Voltage/resistance curve of cuprous-oxide acoustic shock-absorbers. Forward direction at 20° C.

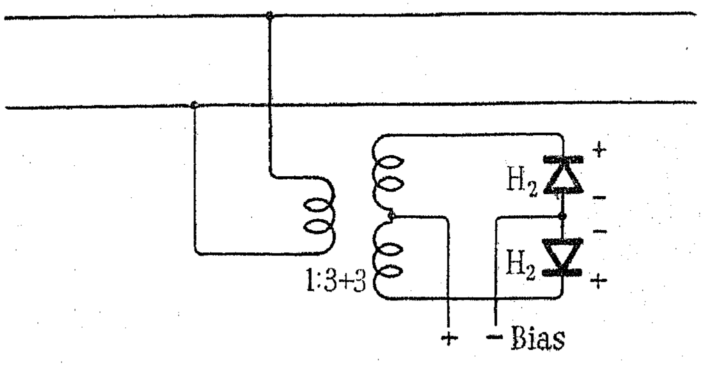


Fig. 21.—Circuit diagram of voltage limiter.

A similar arrangement is used to limit the peak voltage of speech applied to the channels of carrier telephone systems, but in this case a biasing voltage is applied to each rectifier (see Fig. 21). This has the effect of making the limiting action much sharper, since both rectifiers remain practically non-conducting until the peak voltage of the applied speech reaches the value of the biasing potential. The use of this device considerably reduces the inter-channel cross-talk of the carrier system without introducing any degrading effect on the transmission quality.

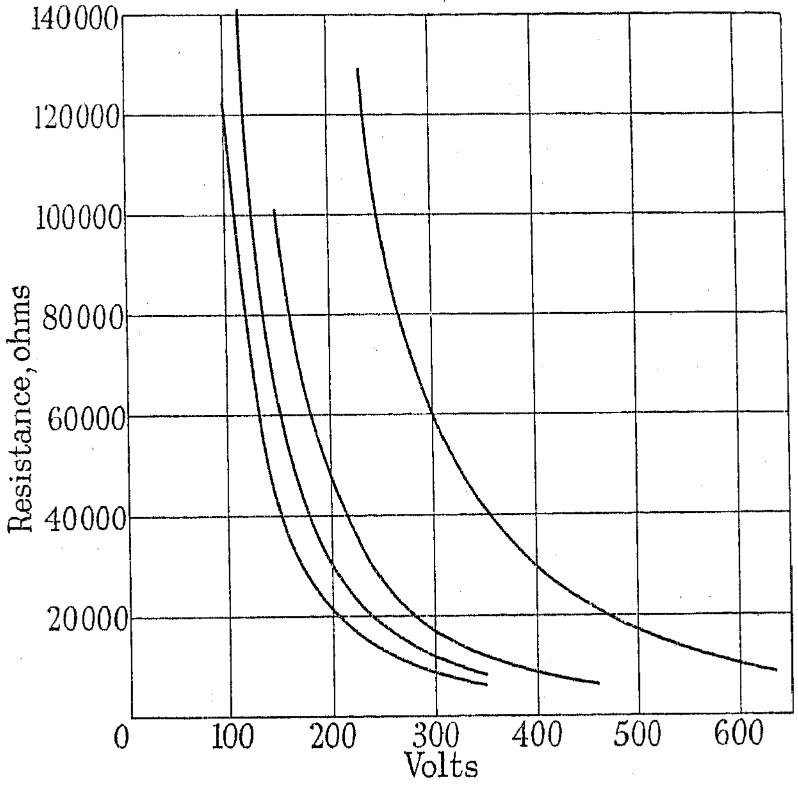


Fig. 22.—Resistance/voltage characteristics of silicon-carbide varistors.

An alternative device, consisting of a neon tube across the secondary of a transformer, the primary of which shunts a telephone circuit, is used in a 12-channel telephone carrier system.

Varistors

As an alternative to the cuprous-oxide rectifier other materials with non-linear resistance characteristics may be used. Such materials are termed " varistors " and are usually composed of compressed silicon carbide. Some typical varistor discs are illustrated in Fig. 19B. In general these units operate at much higher voltages than cuprous-oxide rectifiers and their resistance does not drop as low. Some typical voltage/resistance curves for varistor units of silicon carbide are shown in Fig. 22. The characteristics of varistors so far produced render them unsuitable as acoustic shock-absorbers unless used in conjunction with a step-up transformer.

CONCLUSION

In conclusion let me say that in the time at my disposal it has not been possible to deal by any means exhaustively with the subject of protective devices and I have therefore endeavoured to stress the more unusual features of lightning damage and to spend more time on descriptions of those devices in the research stage of development than on the details of standard designs. Also let me say a reassuring word lest the description of damaged plant tends to alarm certain nervous telephone users. The telephone has been with us for a good many years and there are some 40 million subscribers in all parts of the world, yet I have been unable to find any record of a telephone user being killed or even injured. Also, although line plant may suffer considerable damage the damage to telephones and exchange apparatus is almost negligible.

Finally I should like to take this opportunity of thanking a number of my colleagues for kind assistance in the collection of data and for many helpful suggestions.

WIRELESS SECTION: CHAIRMAN'S ADDRESS

By A. J. GILL, B.Sc.(Eng.), Member.*

(*Address delivered 2nd November*, 1938.)

I propose to review some of the more important developments in radio engineering which have been carried out by the Post Office Engineering Department, or with which that Department has been associated, during the last year or so.

The first item which I have chosen is that of ultra-short-wave telephone equipments.

In the British Isles there are many short routes which are eminently suited for exploitation by ultra-short waves. For example, there are the Straits of Dover, the mainland and Channel Islands, the mainland and Scilly Isles, England to the Isle of Man, England to Ireland, and many possible routes in the Scottish Islands. In some cases submarine cables already exist over these paths, but, owing to the growth of traffic, additional circuits are constantly being required (see Fig. 1).

Equipment for service of this type has been the subject of development for the past 10 years and has now reached an entirely reliable stage.

For short ranges up to about 40 miles a transmitter has been developed giving an unmodulated output of 1 watt at frequencies up to 80 Mc./sec. A crystal-controlled oscillator at a frequency one-quarter of the final frequency controls the transmitter, which is worked from an a.c. supply and can be left unattended. The transmitter can be modulated from 100 to 10 000 c./sec. With this range two telephone circuits are provided in the transmitter by means of carrier channel equipment.

For longer-distance services where only a single circuit is required an amplifier has been designed to follow the above transmitter. This is a linear Class B amplifier which amplifies the modulated signal to give a carrier power of 10 watts unmodulated signal.

These units are designed for standard rack mounting, and with their power packs occupy respectively 14 in. and 17½ in. of panel space. For services over distances of the order of 100 miles there has been produced a transmitter with unmodulated carrier power of 100 watts. This is contained in a cubicle 2 ft. square and 6 ft. high, and is also designed for unattended operation.

The crystal drive unit is similar to the 1-watt transmitter; it is followed by two pentode stages and a stage of balanced triodes of the carbon-anode type.

The order of frequency control is ± 10 parts in 10^6. Anode modulation is used in this transmitter, and 100 % modulation is possible by either of two modulator units:—

(*a*) A 30–10 000-c./sec. modulator with negative feed-back for two speech channels or one music channel.

(*b*) A 15–100-kc./sec. modulator for a multi-channel service.

This latter modulator will allow the radio service to be inserted in tandem with standard 12-channel carrier telephone systems working over the range 12–60 kc./sec. Alternatively it will permit the use of multi-channel equipment produced for the co-axial cable system over the frequency range 60–100 kc./sec. A transmitter of still higher power has been developed for operation on a new service to the Shetland Islands. It is similar to the 100-watt transmitter, but an additional balanced triode stage provides a final unmodulated carrier output of 350 watts up to 80 Mc./sec. Modulation of 30–10 000 c./sec. per sec. is applied to the anode of the final stage.

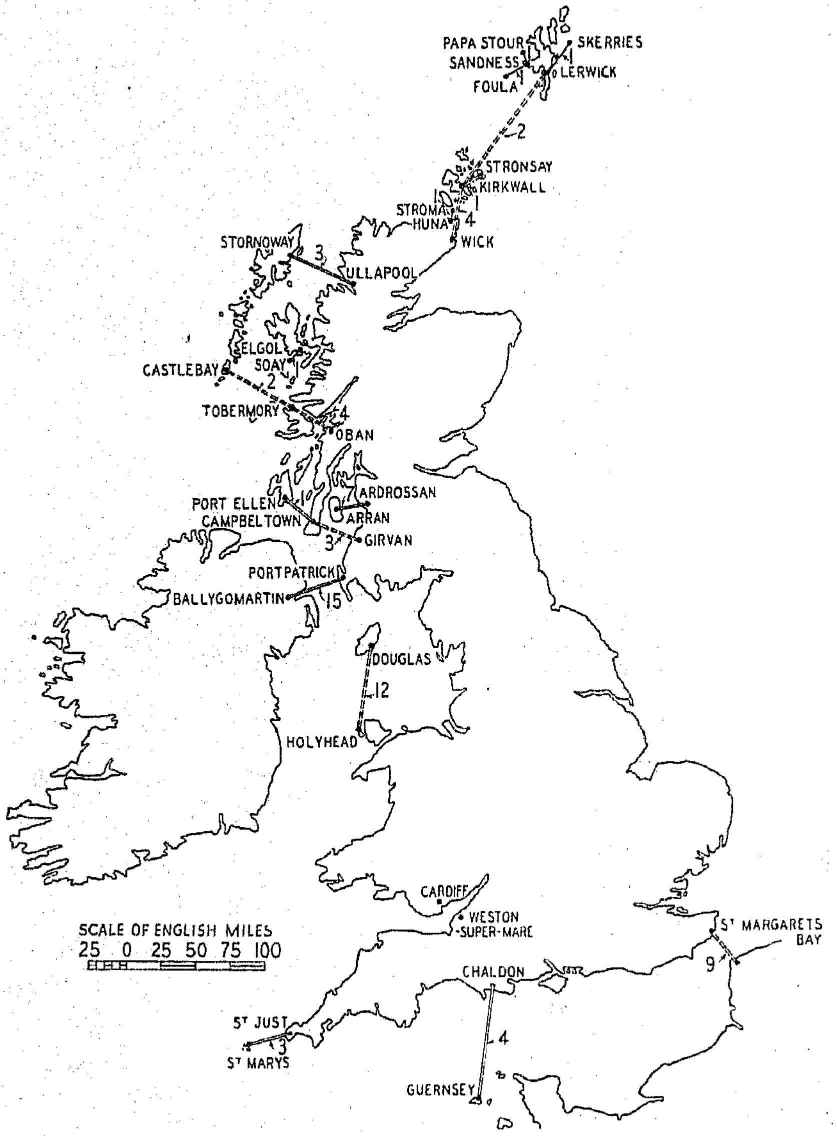


Fig. 1.—Position of G.P.O. ultra-short-wave radio links, 1st February, 1938.

═══ 4-wire trunk circuits (working).
╍╍╍ 4-wire trunk circuits (authorized and/or under construction).
─── radio-phonogram circuits (working).
Figures indicate number of working or authorized circuits.

The receiver used in conjunction with these transmitters is also designed for unattended operation from a 230-volt 50-cycle a.c. supply.

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* Post Office Engineering Department.

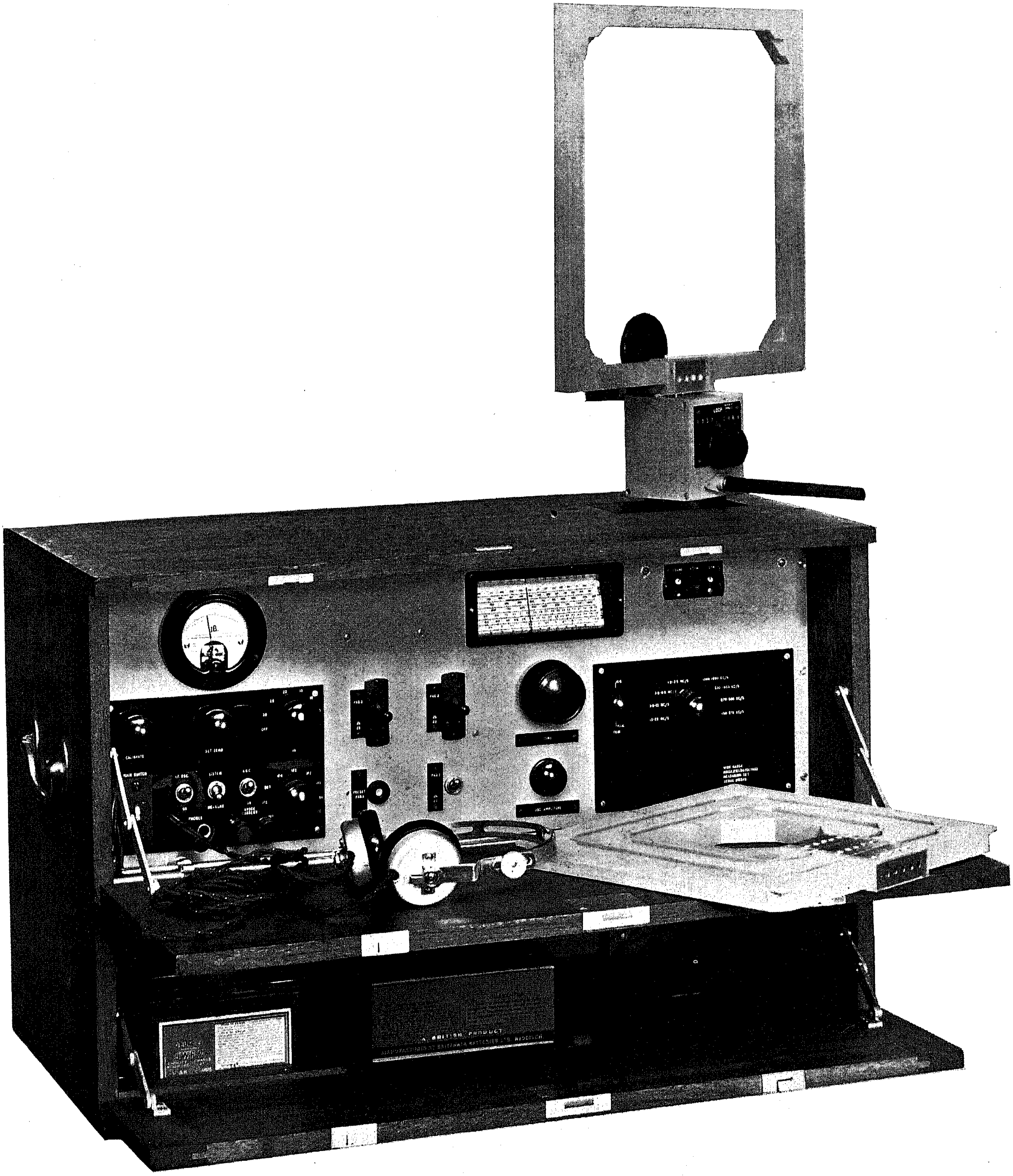


Fig. 3.—Wide-range portable noise-field and voltage measuring set, showing loop aerial for field-strength measurement and direction-finding on 150 kc./sec.–25 Mc./sec.

(*Facing page* 248.)

Plate 2

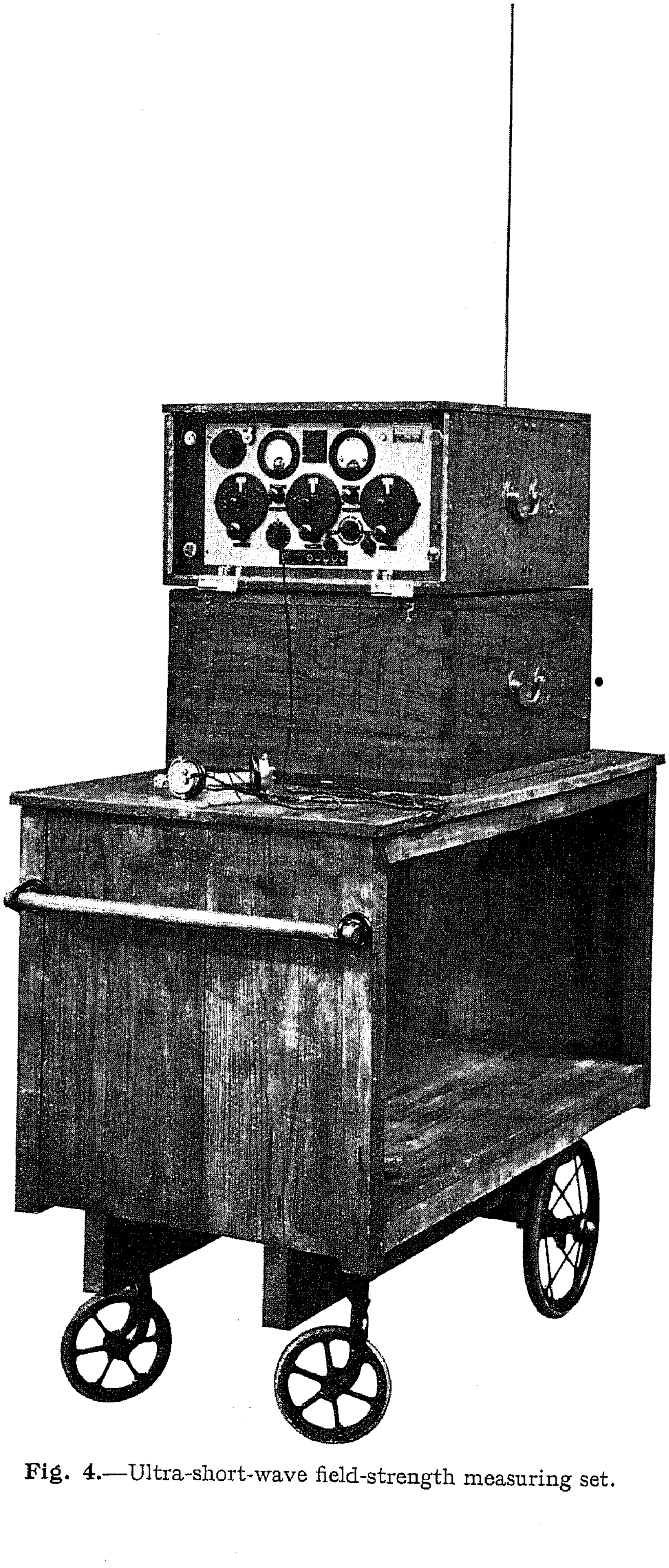


Fig. 4.—Ultra-short-wave field-strength measuring set.

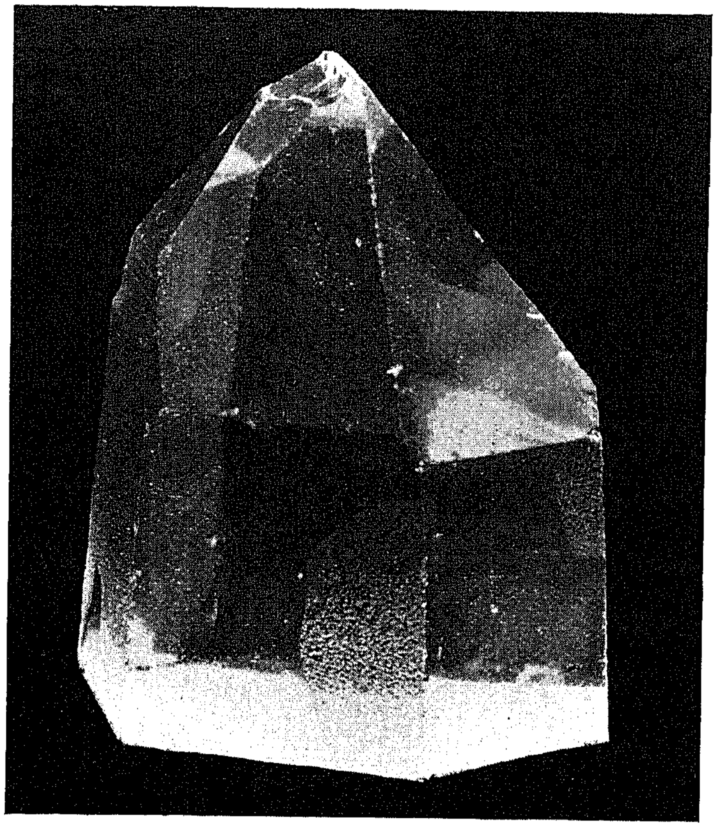


Fig. 6A.—Natural etch pattern on prism and pyramid faces.

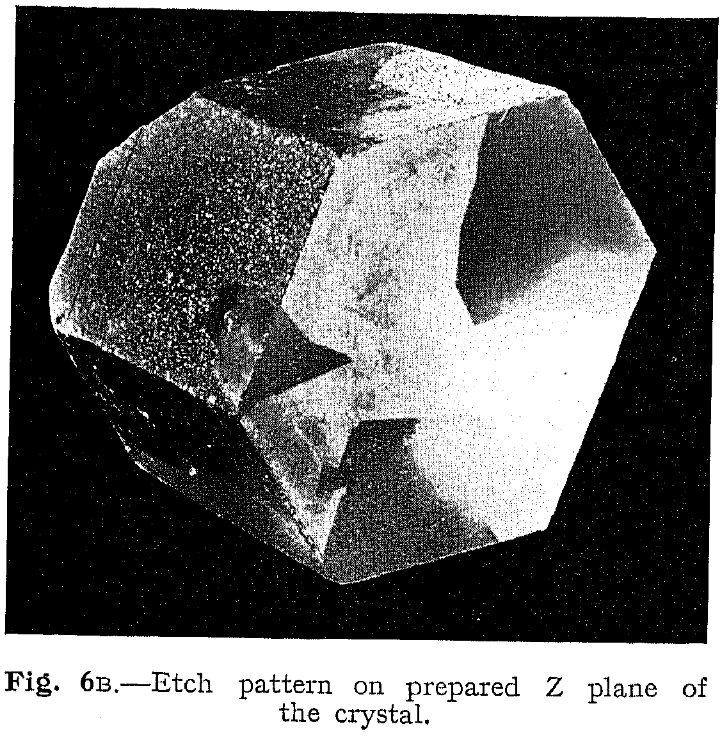
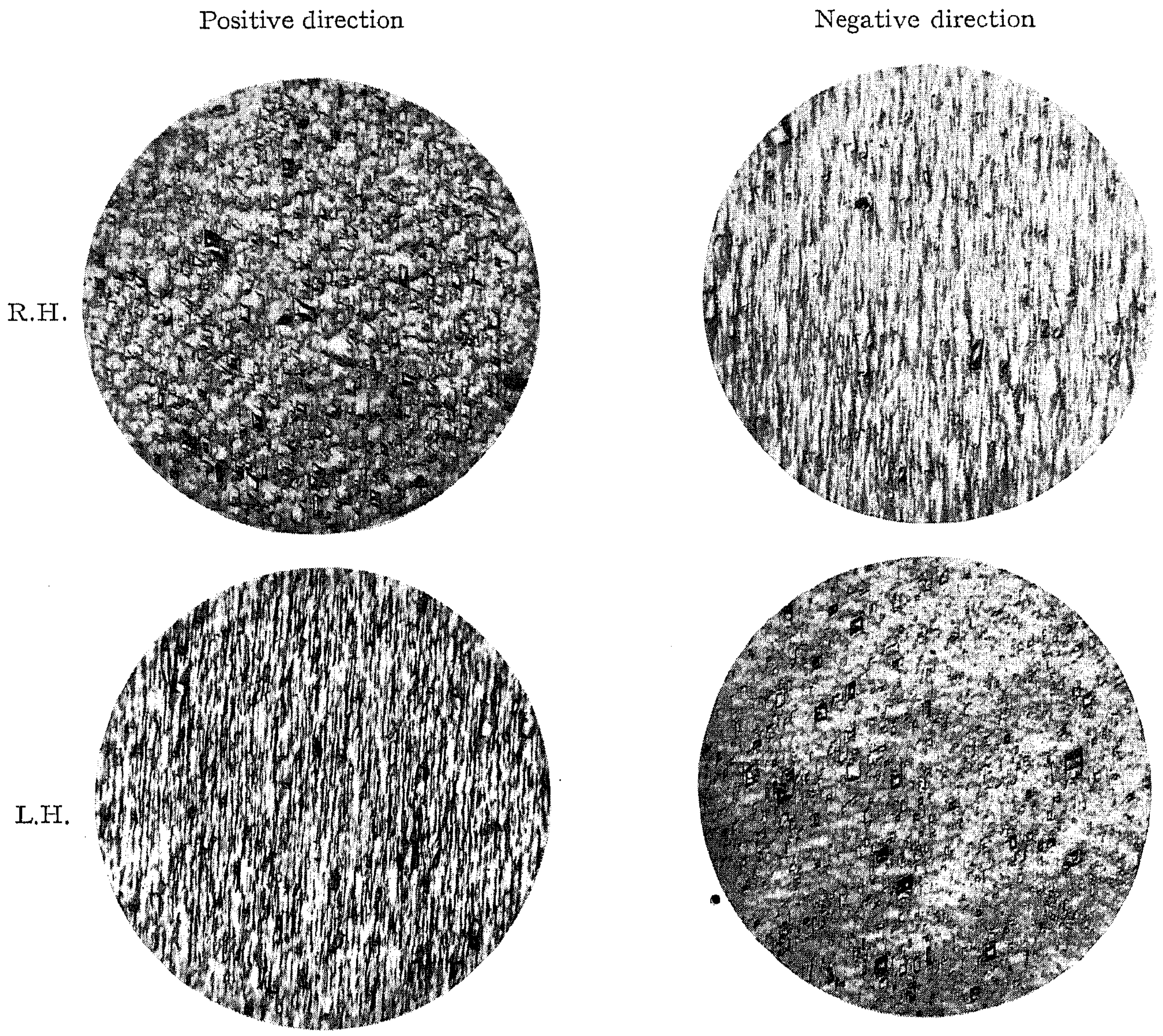
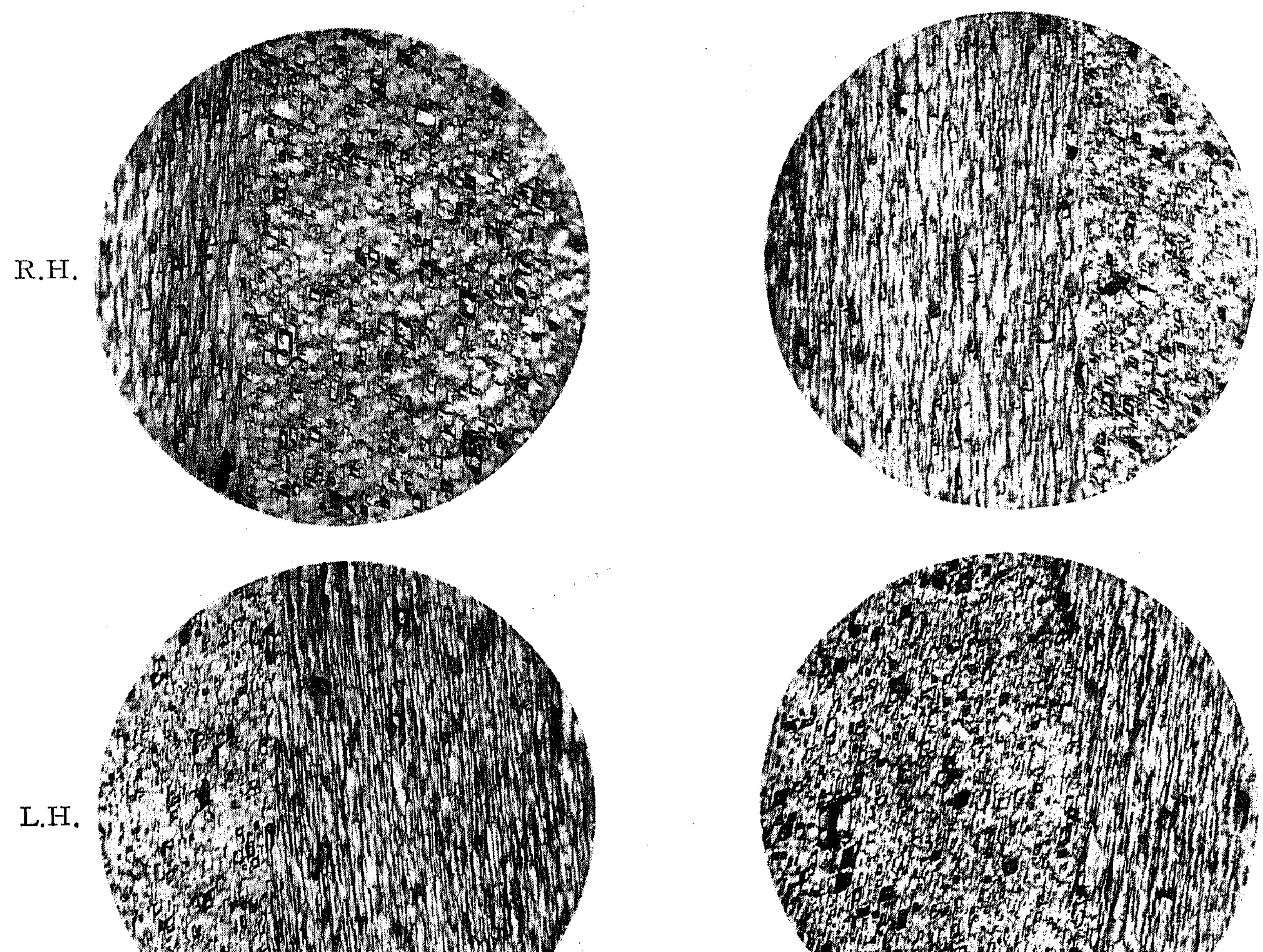


Fig. 6B.—Etch pattern on prepared Z plane of the crystal.

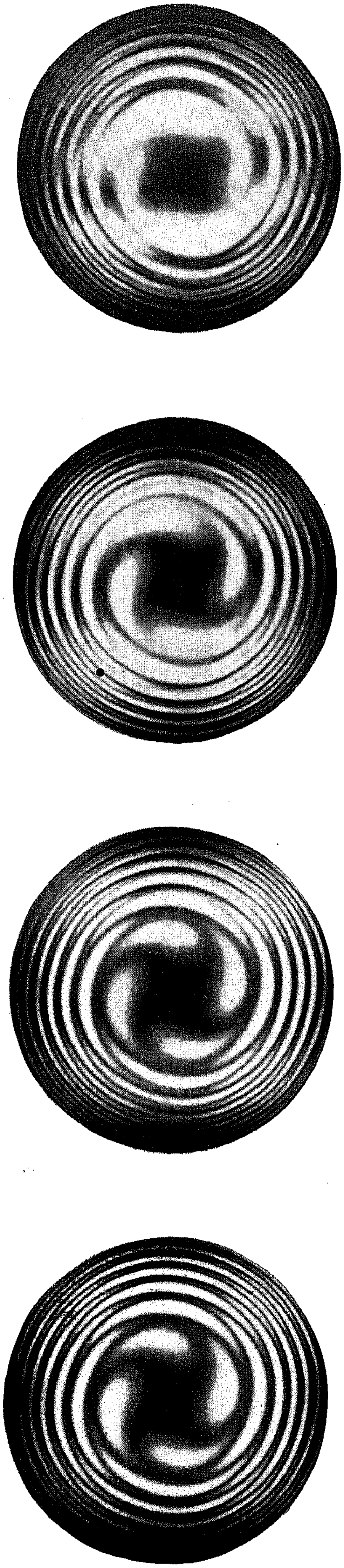


(*a*) Untwinned.



(*b*) Electrical twinning.

Fig. 8.—Etch patterns in X planes. Magnification 120 diameters.



Angle of tilt:—

1 degree

20 minutes

10 minutes

Zero

Fig. 9.—Interference pattern for a trued Z slab in polarized convergent monochromatic light.

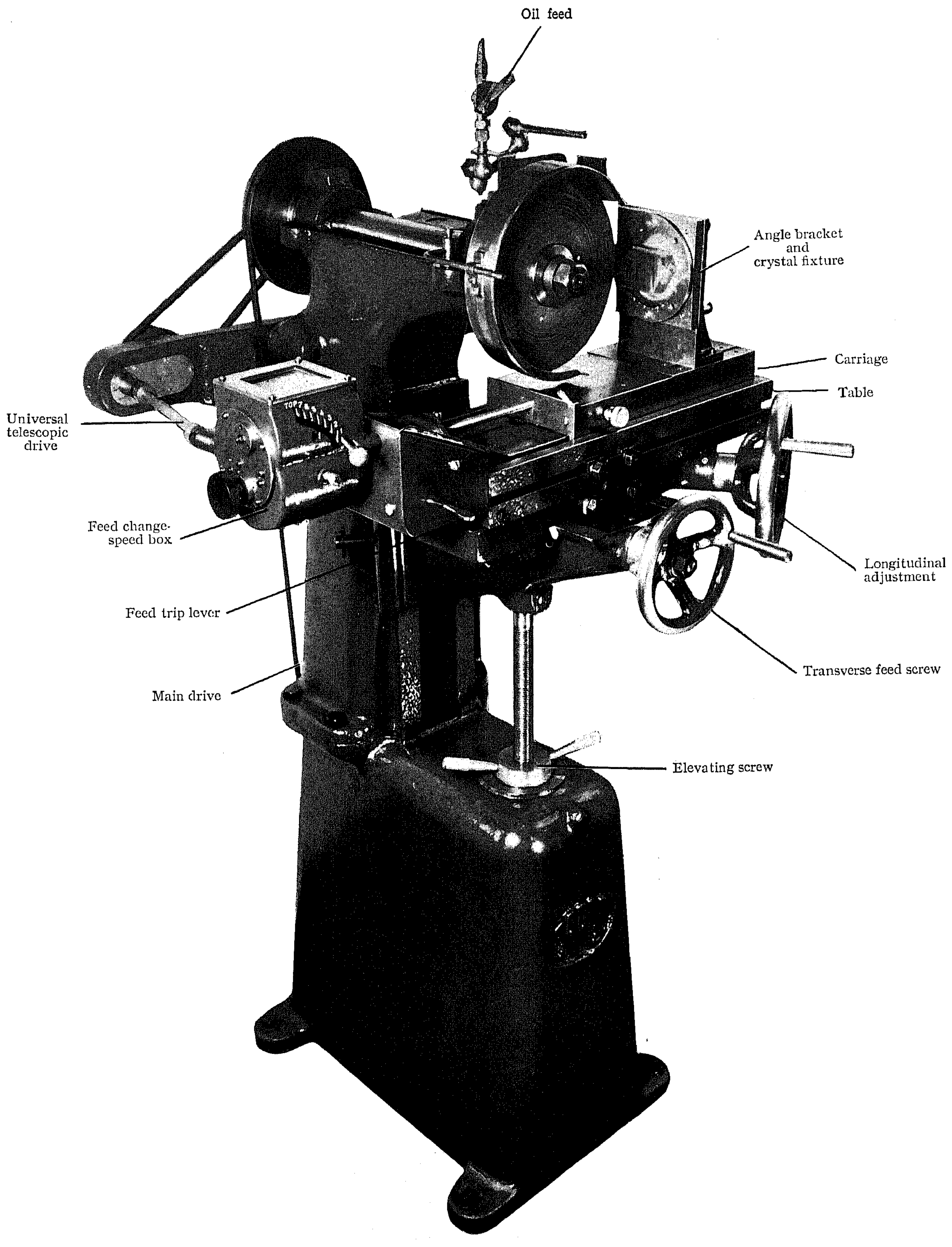
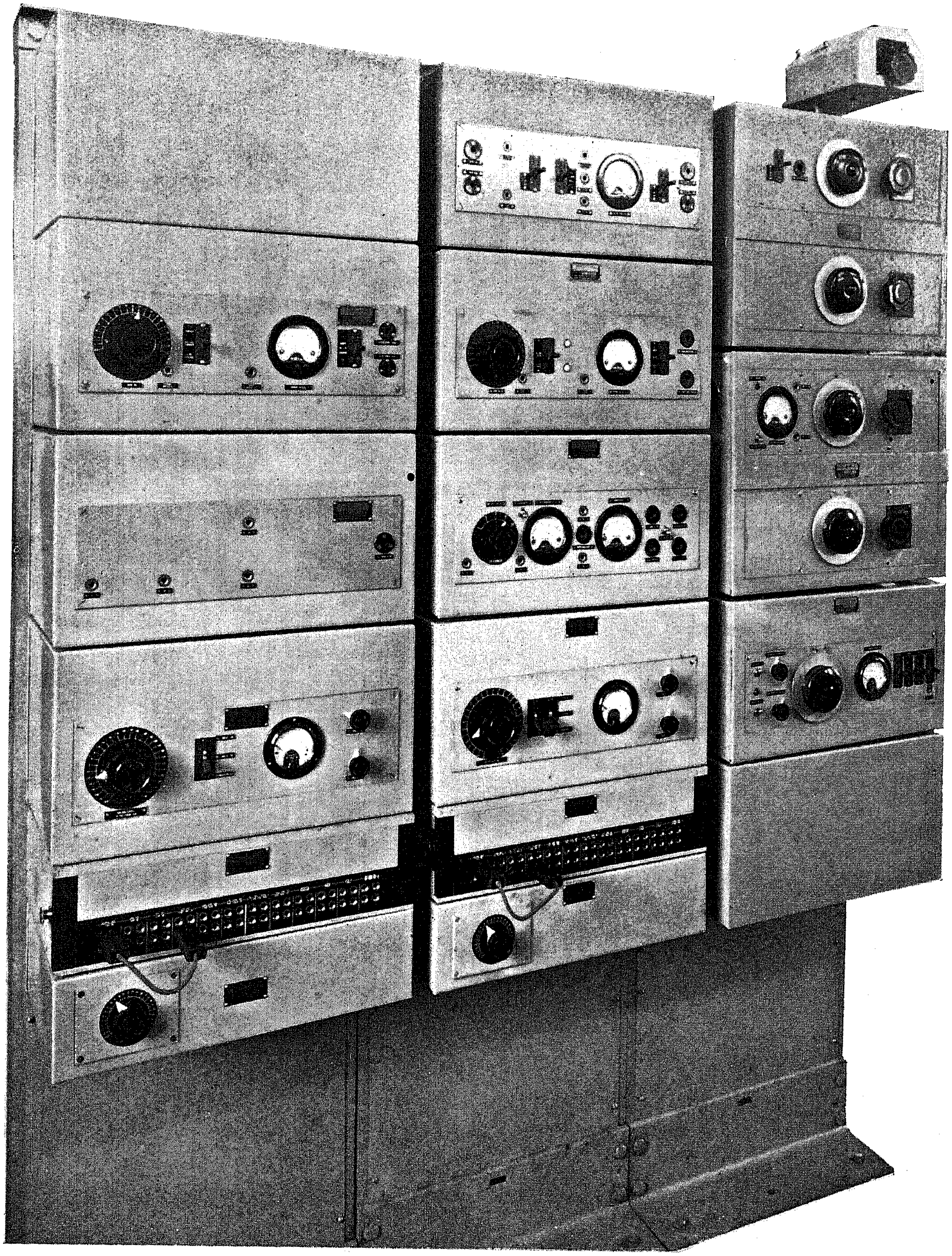


Fig. 10.—Cutting machine No. 2.



Blank
I.F.2 amp^{r} and dem^{r}
Carrier amplifier
Volume indicator
Jack field
Line amplifier
Channel B.

I.F.1 amp^{r} and F.C.2
I.F.2 amp^{r} and dem^{r}
Carrier amplifier
Volume indicator
Jack field
Line amplifier
Channel A.

Antenna switch
H.F. amplifier
Beating oscillator
Test oscillator
Blank

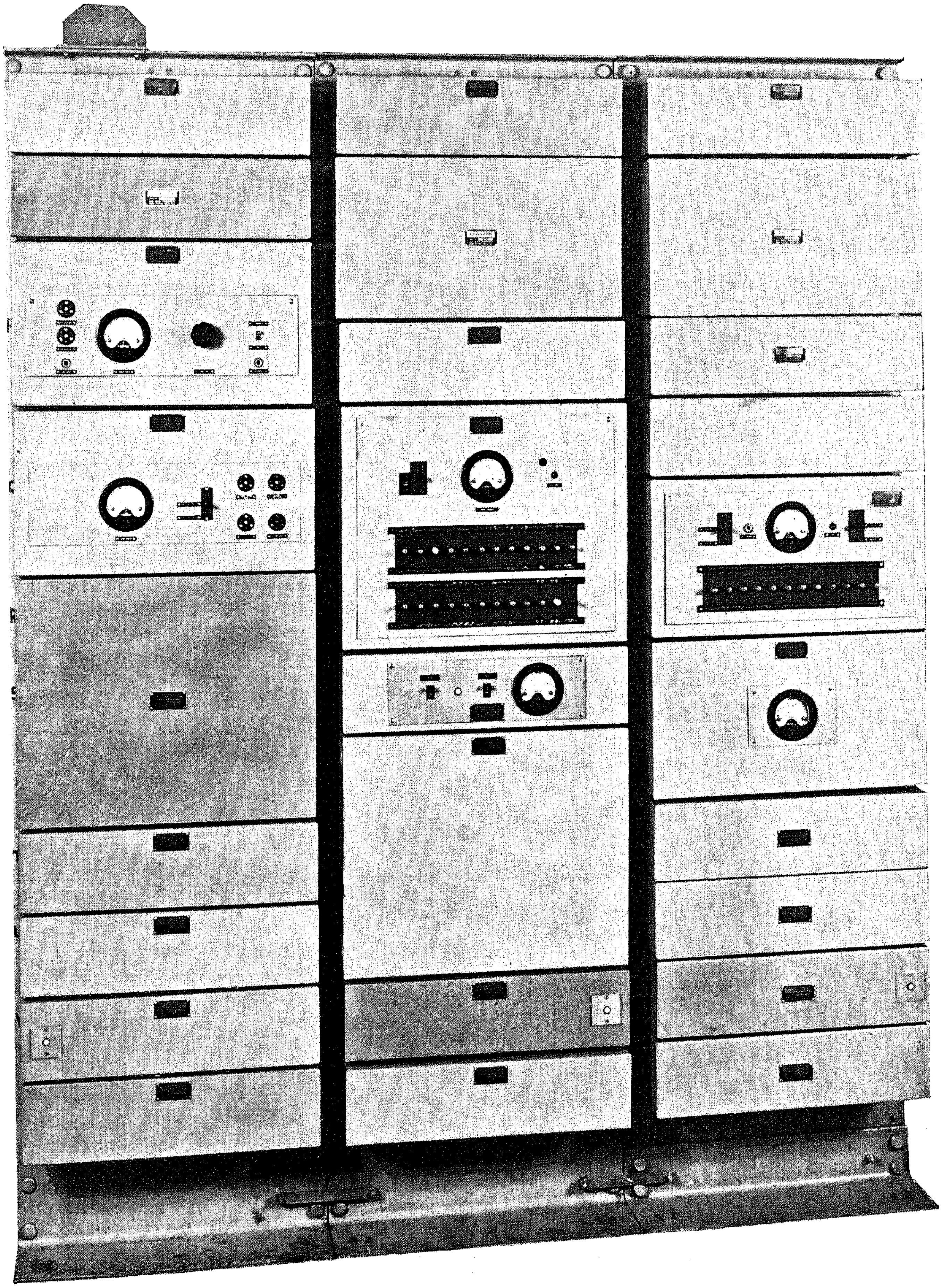
Front view

Fig. 16.—Dual-channel single-sideband radio receiver.

Antenna switch
Tag panel
I.F.1 filter
Frequency-control units 1 and 2
100-kc. osc. and 500 kc., 700-kc. harm. selectors
H.P. and L.P. filters
L.T. supply
L.T. rectifier

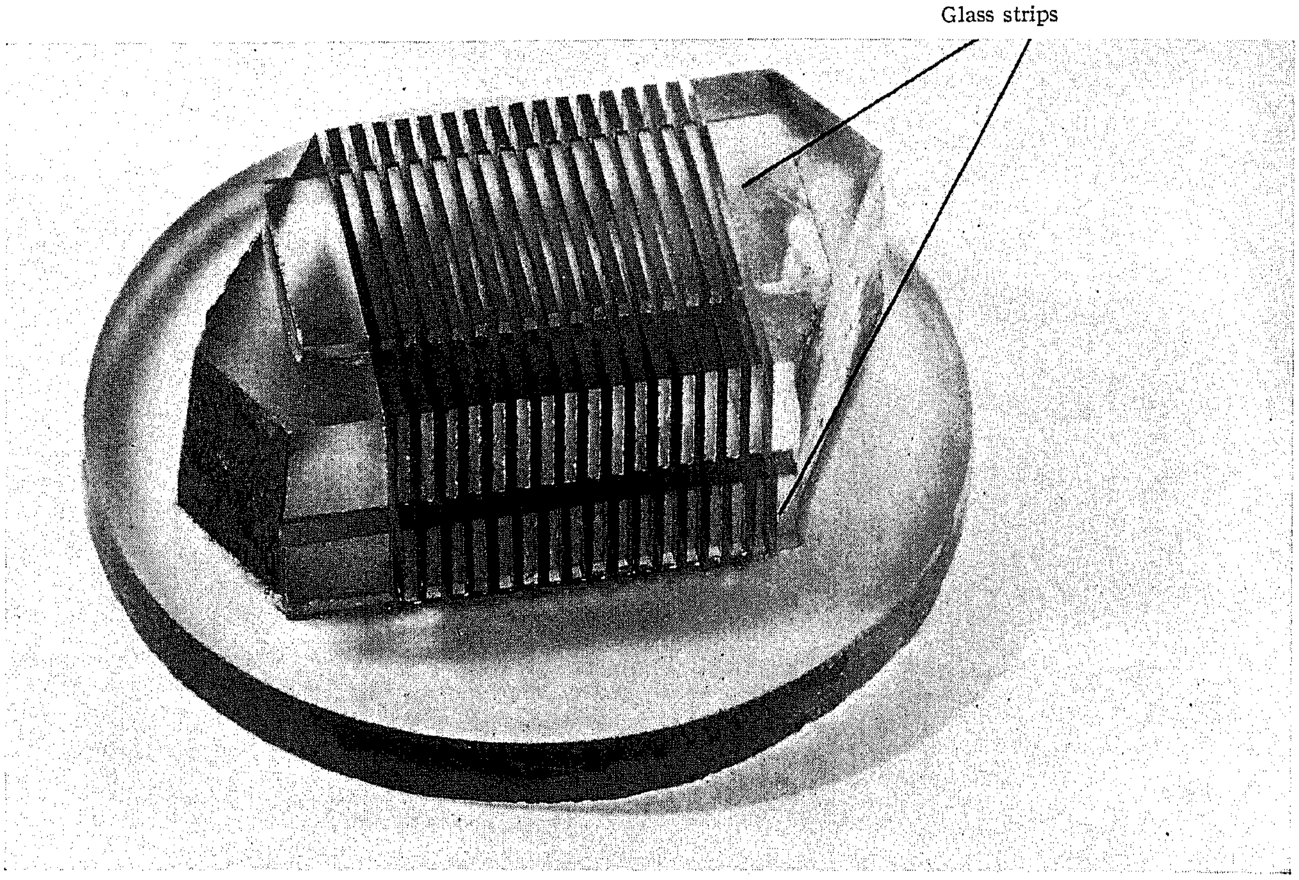
Tag panel
Channel filter
Carrier filter
Key, fuse, and meter panel
Supply panel
H.T. supply
L.T. supply
Line term^n panel

Tag panel
Channel filter
Carrier filter
Blank
Key, fuse, and meter panel
H.T. stabilizer
H.P. and L.P. filters
L.T. supply
Line term^n panel

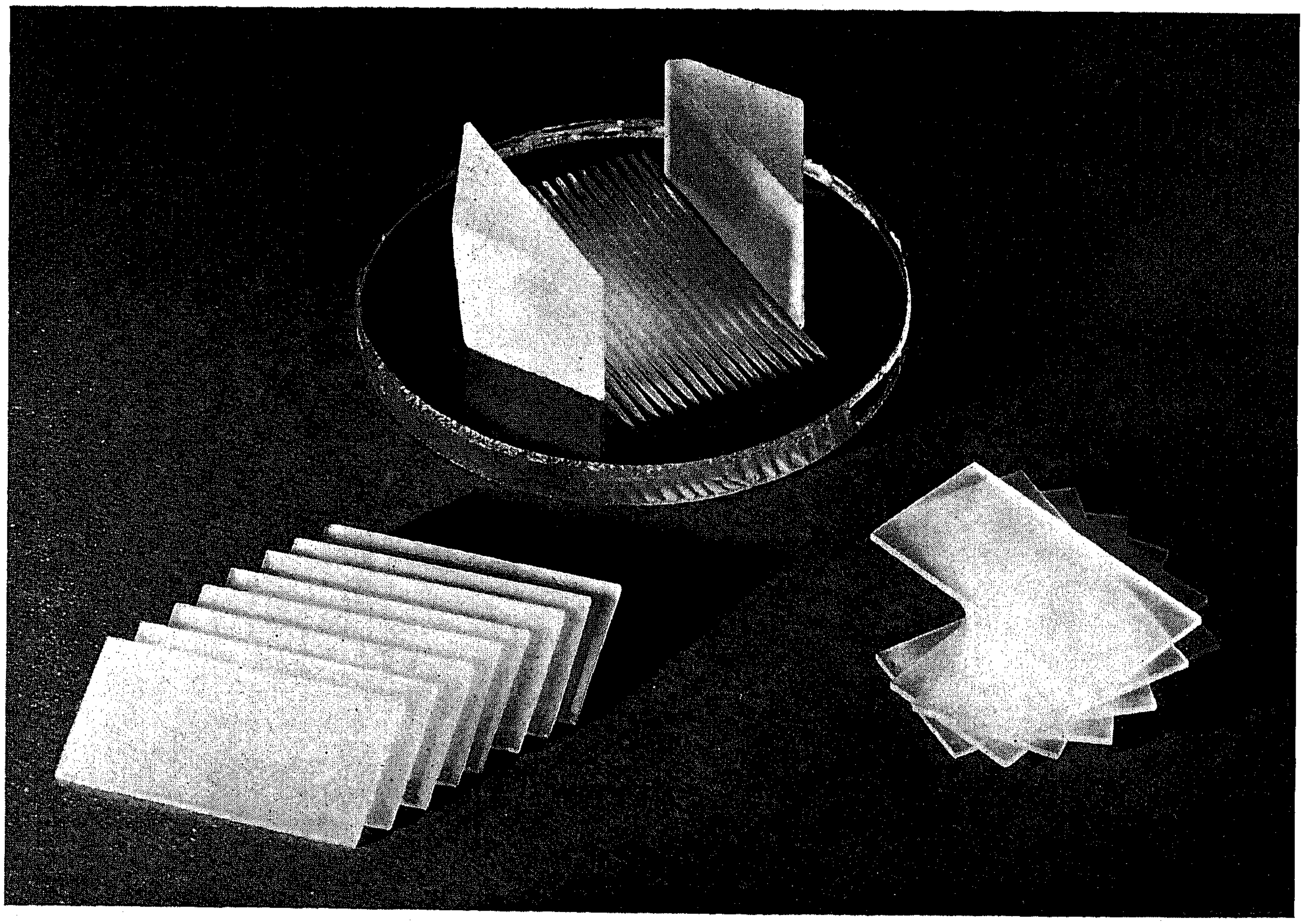


Rear view

Fig. 16 (cont.).



(*a*) X plates in Z slab direct from cutting machine.



(*b*) X plates removed from Z slab and cleaned.

Fig. 11.—Stages in the preparation of X plates.

The receiver is of the superheterodyne type having an intermediate frequency of 3 000 kc./sec. The beating oscillator is crystal-controlled and is similar to the drive unit in the 1 watt transmitter. This feature ensures stability of adjustment over prolonged periods. The audio-frequency response of the normal receiver is uniform from 100 to 10 000 c./sec., but when it is to be used in connection with multi-channel systems working over a wider modulation band the frequency response is suitably widened.

As mentioned previously, these equipments are standardized for a.c. power supplies. Where a d.c. public supply only is available a rotary convertor is used. Where no public power supply is available it is the practice to provide in the higher-powered installations heavy-oil-engine-driven alternators in duplicate. For low-powered installations it is usual to provide a battery, charged intermittently by a heavy-oil-engine-driven generator, together with a rotary convertor.

The equipments described are already in commercial service. In addition, later patterns have been produced for experimental work on higher frequencies up to 150 Mc./sec. (2 m. wavelength). Low-powered transmitters similar to the 1-watt transmitter, but with an output of 0·5 watt with quartz-crystal control, have been constructed and used successfully. For longer-range investigations higher-powered transmitters with a peak output of 100 watts at 144 Mc./sec. are now undergoing test. These sets comprise—

Crystal oscillator on approximately 12 Mc./sec. using a low-frequency pentode-type valve.
1st frequency multiplier (tripler) using a low-frequency pentode-type valve.
2nd frequency multiplier (doubler) using a low-frequency pentode-type valve.
Intermediate buffer amplifier using a low-frequency pentode-type valve.
3rd frequency multiplier (doubler) using 2 R.C.A. 807 ("beam" valves).
Final amplifier using 2 D.E.T. 12 (graphite-anode triodes).

Provision is made for the use of various types of modulators so that investigations can be carried out on telephony, carrier telephony, or television.

A similar development has been necessary in regard to receivers, and the superheterodyne receiver has been modified by the substitution of two acorn pentode valves in push-pull for the first detector. The tuned input circuit is provided by a variable inductor consisting of two parallel copper tubes ½ in. outside diameter and 18 in. long. A short-circuiting bar clamped across these tubes serves as the tuning adjustment. In order to avoid complicating the crystal-driven beating oscillator, the first detector is supplied with a frequency of half the normal value; this proves to be entirely satisfactory. The design of this receiver is such that thermal-agitation noise of the tuned input circuit predominates over other sources of noise, and this condition is a good criterion of performance of any receiver.

The results of propagation studies on these higher frequencies are not yet available, but during the past two years studies have been made on the Channel Islands commercial service working on 37·5 and 60 Mc./sec. between Chaldon (near Lulworth Cove) and Guernsey. The total length of path is 85 miles, and as the elevations of the aerials at Chaldon and Guernsey are 500 ft. and 270 ft. respectively, the path is non-optical. The method of observation gives a continuous graphic record of the received field strength referred to an arbitrary datum (see Fig. 2). The recorder actually plots the anode current of the first stage of the intermediate-frequency amplifier. Owing to the action of the automatic gain control on the receiver, this anode current is a function of the received field strength. For calibration purposes it is assumed that the signal/noise ratio at the output of the receiver is, for constant modulation depth, directly proportional to the received field strength. The actual recorders have accordingly been calibrated in terms of signal/noise ratio for 100 % modulation against recorder currents.

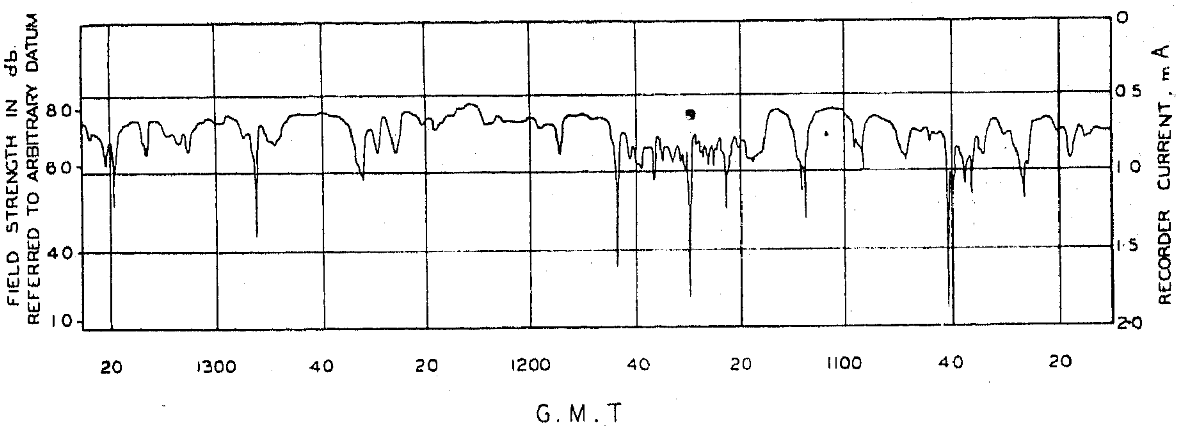


Fig. 2.—Guernsey–Chaldon 5-metre horizontally-polarized transmission. Typical fading record.

The records obtained over the past two years show that considerable fading exists on both the 37·5- and 60-Mc./sec. transmission, being more severe on the higher frequency. The depth of fades is under exceptional circumstances as much as 60 db., resulting in complete "wipe out" of the received field. Normal fading of 30 to 40 db. is compensated approximately by the automatic gain control of the receiver. The duration of the fades is usually short, and very little deterioration of the traffic-handling capacity of the circuits from this cause has been observed.

Endeavours have been made to correlate the field changes with meteorological conditions, but without success. Since it is concluded from general observation that the propagation of ultra-short waves over non-optical paths is due to diffraction and refraction as distinct from reflection from ionized layers in the upper atmosphere, it is to be expected that some dependence on meteorological conditions would be observed. The failure to establish such a relationship is probably due to the meagre data available on the conditions obtaining over the path, as meteorological data are available for the terminal points only. It is interesting to note that during the period of intense sunspot activity in the early part of 1938 no departure from the normal propagation conditions was observed on the Chaldon–Guernsey link. On the 60-Mc./sec. circuit, however, the range of fields was 78 db. to 0 db. (relative to 1 μV/m.) in the spring of 1938, compared with 50 db. to 0 db. in the spring of 1937. On the 37·5-Mc./sec. circuit the range of fields was the same in both years, viz. 70 db. to 0 db.

In connection with the investigations of propagation and interference the Post Office produced a portable field-strength and voltage measuring set. The set (see Fig. 3 on Plate 1, facing page 248) is a superheterodyne working on an intermediate frequency of 450 kc./sec., and it has a working range of from 150 kc./sec. to 25 Mc./sec. (2 000–12 m.). The calibration of the set is checked by adjusting the gain to produce a known output from the thermal noise in the first tuned circuit when tuned to a frequency of 240 kc./sec.

The apparatus is arranged for measuring voltages and field strength, the latter with either a frame or vertical rod aerial. The frame aerial may be rotated in a " plug-in " socket, providing simple direction-finding facility. The output circuit includes a meter and telephones with a short time-constant detector for listening and a long time-constant for measurement purposes. The latter conforms to the recommendations of the C.I.S.P.R.* for interference measurements. Automatic gain control is provided for short-wave listening. The receiver sensitivities are approximately 10 μV/m. for voltage measurements and 10 and 200 μV/m. for field-strength measurements, using the vertical-rod and frame aerial respectively. A total attenuation of 90 db. is provided in the intermediate frequency.

The receiver has proved very useful, and the design has been freely communicated to manufacturers, with the result that there are now a number of sets of similar type available on the market.

In view of the work which had been in progress on ultra-short waves it was decided to develop a similar type of set for measurements in this range. As a basis the previously-described superheterodyne commercial receiver was taken, the crystal-controlled beating oscillator substituted by a stable variable-frequency oscillator, and an attenuator provided in the intermediate-frequency circuit of 100 db. in 5-db. steps (see Fig. 4 on Plate 2).

The frequency range of the receiver is from 20 to 75 Mc./sec., and its sensitivity is 10 μV/m. and 2 μV/m. for voltage and field-strength measurements respectively. For voltage measurements a length of co-axial cable approximately 10 ft. in length is used to apply the unknown voltage to the measuring set. The impedance at the input end of the cable is arranged to be greater than 1 000 ohms with one terminal at earth potential.

For field-strength measurements a rod aerial is used. This may be fixed in a vertical or horizontal direction. With the horizontal aerial the receiver may be used for approximate direction-finding purposes.

The output circuit is similar to that of the 2 000–12 m. set. Both sets must of course be calibrated initially from some standard source of voltage and field. On the lower-frequency set this is done by means of a standard-type field-strength-measuring set provided with a comparison oscillator and attenuator. The ultra-short-wave set can be calibrated in the same way or by means of a computed field set up by a horizontal loop aerial carrying a known current, a method introduced by the National Physical Laboratory. The novelty feature of these sets is of course the application of the thermal noise method of calibration to these higher frequencies. The facility of checking the calibration without the use of a separate comparison oscillator simplifies the set and increases its portability.

One of the most serious sources of interference on ultra-short waves is the ignition systems of internal-combustion engines. This subject was dealt with in a recent paper* read before this Section.

Experience indicates that interference with commercial traffic can be appreciable if the source of interference is within ¼ mile of the receiving aerial.

Vertically-polarized receiving systems are much more susceptible to ignition interference than horizontally-polarized systems. In one typical case, where a road passed before the receiving aerial, a reduction of interference by 25 db. was attained by changing over the transmission from vertical to horizontal polarization.

Qualitative observations indicate that ignition interference is considerably reduced as the wavelength is reduced from 5 m. to 2 m., and this is an incentive to pressing forward the development of equipment for the use of these shorter waves.

In radio-telephone circuits used for public traffic some degree of privacy is desirable to hinder accidental or intentional eavesdropping. Most types of privacy equipment in use for longer-distance services are relatively expensive, and endeavour has been made to produce something simpler but effective. Where a number of radio-telephone circuits exist over a route it has been found possible to employ a channel-switching privacy system. This system changes the line circuit associated with a particular radio circuit every few seconds, with the result that a receiver tuned to the radio circuit produces an output consisting of jumbled scraps of several conversations.

In one system of this kind in actual service provision is made for switching six go and return radio channels between six 4-wire telephone circuits.

Automatic telephone type uniselectors are employed for the actual switching operation. The uniselectors are fitted with bridging wipers so that all circuits are short-circuited while the change-over is taking place. Synchronism of the switching at the two ends of the radio channels is obtained by the use of a single control tone operating over a separate radio channel to and from the controlling station. This tone, operating through relays, energizes the drive magnet of all the uniselectors. Chain contacts on the selectors cause the tone to be returned to the control point only when all the drive magnets have been energized. The return tone after passing through a timing circuit cuts off the original source of tone so that all drive magnets are released simultaneously and the wipers step one contact. The process is then repeated, the frequency of operation being determined by the setting of the timing circuit. The operation of the switches is normally imperceptible to persons talking over the circuits.

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* Comité International Spécial des Perturbations Radiophoniques.

* A. J. GILL and S. WHITEHEAD: "Electrical Interference with Radio Reception," *Journal I.E.E.*, 1938, vol. 83, p. 345.

Leaving the subject of ultra-short waves, I now propose to say a few words on a development relating to frequency measurements and piezo-electric quartz crystals.

The improvements affected in frequency standards during the past 15 years have been considerable, and whereas a precision of measurement of ± 100 parts in 10^6 was exceptional in 1923 the corresponding orders for 1928 and 1933 were ± 10 parts and ± 1 part in 10^6 respectively. To-day it is possible to measure to ± 1 part in 10^7, and in the near future it will be possible to work to ± 1 part in 10^8.

The development of methods of precision measurement of frequency in the Post Office became necessary because the Post Office is the authority responsible for the allocation of wavelengths in this country and it had to possess means to determine whether stations are working on their allotted frequencies, and when interference arose between stations it had to be in a position to determine which station was off its frequency. Other requirements, however, have since led to advances in equipment beyond those demanded for ordinary station measurements. The Post Office standards comprise two valve-maintained elinvar forks working at 1000 c./sec. and one quartz-controlled oscillator working on 1 000 kc./sec., all of which are maintained in conditions of constant temperature and barometric pressure. The provision of a second quartz-controlled oscillator of a different type working on a frequency of 100 kc./sec. is in hand.

The frequencies of the oscillators are determined daily in terms of mean solar time.

The Post Office standards, which are housed at the Dollis Hill Experimental Station, are compared at monthly intervals with the standard of the National Physical Laboratory, the comparison being effected by means of the 1 000 c./sec. transmitted as a modulation from the Teddington transmitter on a carrier of 396 kc./sec. The agreement between Teddington and Dollis Hill is normally within ± 1 part in 10^7. On occasions, when local conditions of reception permit, opportunity is taken to compare the local standard with the calibration signals transmitted from Washington by the Bureau of Standards. Again the agreement between the two is within ± 1 part in 10^7.

Frequency-multiplying and measuring equipment associated with the standard enables the ultimate accuracy to be translated to any frequency in the spectrum up to 75 Mc./sec. The method employed for such translations have been already described elsewhere and will not be repeated. The equipment used for this purpose at Dollis Hill is contained on 12 bays of racks and includes comparison signal oscillators for field-strength measurements, audio-frequency amplifiers for dealing with incoming land-line signals, and a long-wave receiver for time-signal reception. Although the present precision has been obtained by means of elinvar tuning forks it seems probable that advances to higher precision in the future will be made by means of quartz oscillators. The advantages of quartz are:—

(*a*) The lower frequency/temperature coefficient it is possible to obtain with quartz, as compared with up to ± 10 parts in 10^6 per 1 deg. C. for the fork, depending on the alloy.

(*b*) The comparatively simple mounting system which is possible with the crystal.

(*c*) The absence of any serious ageing effect. In elinvar, ageing occurs over a period of many years with consequent slow frequency drifts.

The crystal to be used as a standard should be of one of the zero frequency temperature-coefficient type, and its mode of vibration must be such as to permit of a nodal plane suspension. Three main types of crystal are therefore available—the ring operating on an overtone of a circumferential mode, the bar oscillator, and the plate. The upper frequency limit of the first two types is about 100 kc./sec. and of the last type about 1 000 kc./sec.

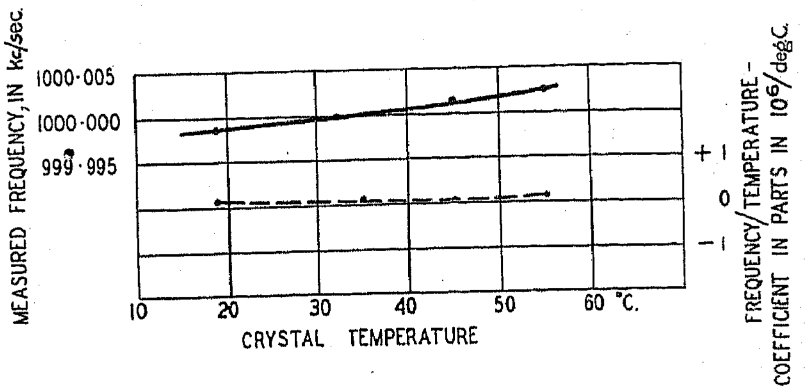


Fig. 5.—Frequency/temperature curve of 1 000 kc./sec. standard crystal mounted in 6 A holder.

The 1 000-kc./sec. crystal used as a standard is a rectangular plate of sensibly zero frequency temperature-coefficient. It oscillates in a shear mode and is clamped in the nodal plane mounted in a partially evacuated holder, a double air-gap being employed. The drive circuit employs a pentode drive stage resistance-coupled to a pentode buffer stage; a number of independent 75-ohm outputs are available from an output transformer. The power supplies, obtained from floating batteries, are stabilized.

The frequency/temperature curve of the crystal is given in Fig. 5, from which it will be observed that the average coefficient of the mounted crystal over the temperature range 19° to 55° C. is only 11 parts in 10^8 per deg. C. The frequency-standard equipment installed at Dollis Hill is not now used for checking the frequencies of transmitting stations, except in the case of transmitters sending out standard frequency transmissions or other special emissions such as international comparisons of standards. The work of checking normal transmissions increased so much that it became necessary a few years ago to establish a separate station for the purpose, manned throughout the 24 hours. Until recently this station was at Colney Heath and formed part of St. Albans Telegraph Receiving Station. Within the last few months it has been transferred to more commodious quarters at Baldock. The function of the station is to determine where the error lies in the cases of interference where British stations are involved, and also whether British stations are conforming to international regulations by maintaining the emitted wave within the limits of frequency tolerance. This work does not demand measurements of the maximum precision now possible. The equipment at Baldock, therefore, is not designed to give such a continuously high standard of precision as that at Dollis Hill, but means are provided for immediate comparison with Dollis Hill by land-line connection.

A great stimulus has been given to the production and use of quartz bars by recent developments in carrier telephony. Whereas the whole of the Post Office requirements for crystal oscillators for the purpose of frequency stabilization can be counted in hundreds, the demand for crystal resonators for the full equipment of a single co-axial cable may exceed 10 000.

The crystal laboratory at Dollis Hill is concerned with the development of production technique for quartz plates for frequency standards, sub-standards, fixed and mobile transmitters, and crystal filter resonators, and it may be of interest to say a few words about the work of this laboratory.

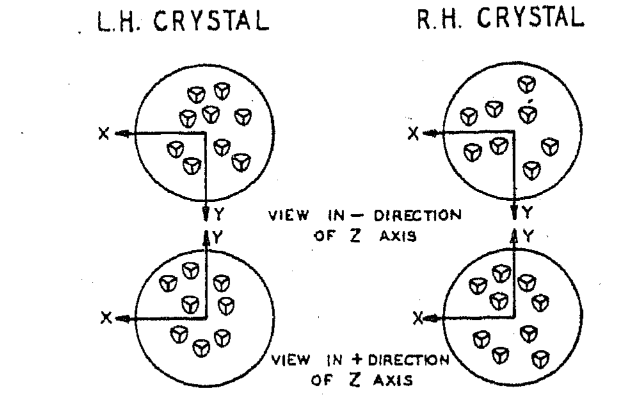
The first problem concerned with crystal production is the selection and grading of the raw material. Unfortunately, the crystal suffers to a considerable extent from two main defects, "twinning" and internal flaws, and the presence of either fault precludes the use of the crystal for the above-mentioned piezo-electric purposes. Flaws can usually be detected by careful examination, but although twinning (a lack of homogeneity in the molecular structure) may be apparent from natural etch patterns on the crystal faces, or from discontinuities in the texture of the face (see Fig. 6 on Plate 2), this is not always the case and recourse to cutting and acid etching is usually necessary before the quality of the material can be determined.

A comprehensive analysis of twinning faults has been made at Dollis Hill, and etching technique has been developed for the determination of the presence of the three twinning forms, optical, electrical, and combined electrical and optical. The characteristic etch patterns for untwinned and the three varieties of twinned left- and right-hand quartz in the X, Y, and Z planes for both viewing directions are shown in Fig. 7. The X-plane etch patterns for untwinned and for electrically twinned left- and right-hand quartz for both viewing directions are illustrated by the photo-micrographs in Fig. 8 (see Plate 3).

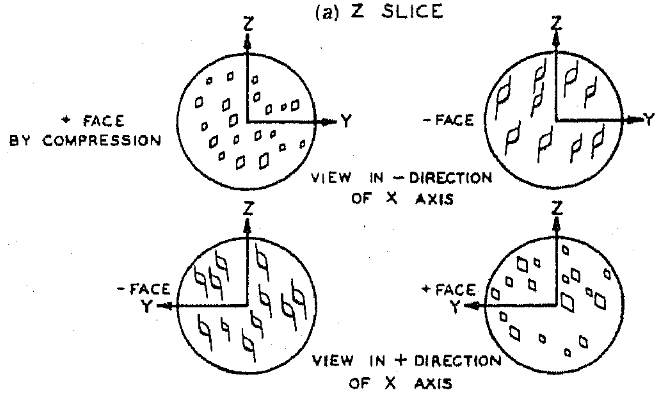
The best supplies of natural quartz consist of large crystals having well-defined faces and whose crystallographic axes can be readily identified. There is, however, a large amount of material available in which the natural faces have been partially or completely destroyed. To permit the use of this inferior material methods have been developed for identifying the crystallographic axes in such samples when not even a portion of one natural face exists.

The performance of the apparatus employed for the determination of the Z axis of a Z slab is clearly demonstrated in Fig. 9 (see Plate 4), which shows the effect of decreasing inaccuracy of alignment on the interference patterns.

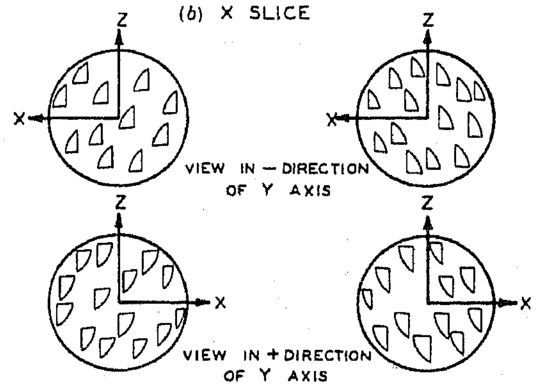
Machines have been designed for the speedier and more accurate cutting of crystals. One of these machines is shown in Fig. 10 (see Plate 5), and the accuracy and economy of the cutting process is clearly demonstrated in Fig. 11 (see Plate 8), which shows photographs of a Z slab which has been sliced into X plates. In Fig. 11(*a*) the plates have not been removed from the glass disc to which they are cemented by special wax, while in Fig. 11(*b*) they have been removed and cleaned.



(*a*) Z SLICE



(*b*) X SLICE



(*c*) Y SLICE

Fig. 7.—Characteristic etch patterns on the X, Y, and Z planes of R.H. and L.H. quartz.

The plates of quartz are finished by lapping processes, and a large saving of time and labour can be effected if the plates cut on the machine are very close to the final dimensions.

Mention has already been made of plates of sensibly zero frequency temperature-coefficient. In these plates the angle of cut is so adjusted that the resultant of the individual coefficients of e, c, and ρ, in the solution of the equation $f = \frac{1}{2e}\sqrt{\frac{c}{\rho}}$ [which gives the frequency of plate in terms of e (thickness), c (elastic coefficient), and ρ (density)] is reduced to zero. In fact zero-coefficient crystals can be produced in the continuous range 50 to 25 000 kc./sec., and frequency/temperature curves of four representative plates having frequencies of 100, 2 750, 4 767, and 15 482 kc./sec. are given in Fig. 12. It should perhaps be pointed out that the attainment of the absolutely zero coefficient is difficult and individual attention on each plate is necessary. The curves shown are for plates which have not received this individual adjustment.

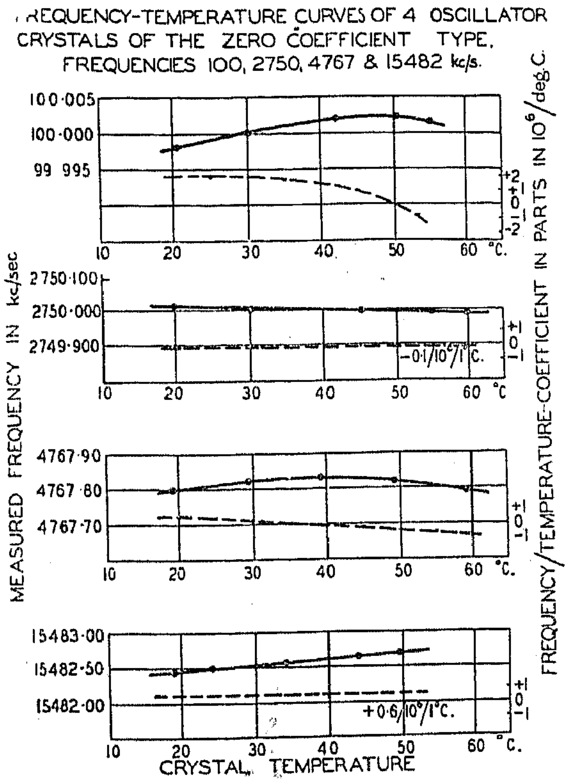


Fig. 12.—Frequency-temperature curves of 4 oscillator crystals of the zero-coefficient type. Frequencies 100, 2 750, 4 767, and 15 482 kc./sec.

The production of plates of frequencies greater than about 10 Mc./sec. is one which calls for a very high degree of skill. The plates are extremely fragile, a zero-coefficient plate of frequency 20 Mc./sec. may have a thickness of only 0·12 mm., and a high degree of face parallelism is essential for satisfactory oscillators. Plates of frequencies up to 25 Mc./sec. have been made, but the commercial limit is considered at the moment to be about 20 Mc./sec.

An interesting application of the high-precision quartz oscillator has been in connection with common-wave broadcasting. At the request of the British Broadcasting Corporation the Post Office undertook to provide a number of quartz oscillators in the range 668 to 1 149 kc./sec., capable of maintaining a frequency constancy of ± 1 part in 10^7. As a preliminary to this work a careful investigation was made into the effects of variation of a number of circuit components and of supplies in the frequency of a 1 000-kc./sec. crystal drive. The results of the investigation and the methods adopted to avoid the effects of the variations are given in Table 1.

A number of the crystals have been completed and brought into use. Three crystals of frequency 1 149 kc./sec. have been employed to drive the Scottish National, Northern National, and London National transmitters. Methods of comparing the frequencies of these crystals have been developed by the British Broadcasting Corporation, to whom I am indebted for the results of tests. The crystal at the North National station (Moorside Edge) has been regarded as the reference crystal,

Table 1

List of Factors Affecting Frequency of 1 000-kc./sec. Crystal Oscillator, Arranged in order of Importance

Factor	Artificial change of factor	Corresponding frequency change	Method of stabilizing factor	Estimated residual change of factor	Corresponding frequency change
Cathode-heater supply voltage	± 5 %	$\mp 3\cdot5/10^8$	Compensated mains transformer	$< \pm 0\cdot25$ %	$\mp 1\cdot7/10^9$
Anode supply voltage	± 5 %	$\pm 3\cdot5/10^8$	Compensated mains rectifier and stabilovolt	$< \pm 0\cdot1$ %	$\pm 0\cdot7/10^9$
Temperature of crystal and holder ..	± 1° C.	$1/10^7$	Thermostatically-controlled oven	$< \pm 0\cdot01$° C.	$< \pm 1/10^9$
Grid resistor	1 MΩ to 5 MΩ	$1/10^6$	Good-quality component	$< \pm 1$ %	$< \pm 1/10^9$
Grid capacitor ..	20–30 μμF	$\pm 7/10^6$	Good-quality components, thermostatically controlled	Negligible	
Valve replacement ..	Another of same type	$7/10^7$	Matched valves available	Negligible	
Load changes	Extremely wide	$< 1/10^7$	Buffer stage	Negligible	
Anode-circuit tune (normal value 227 μμF	1 μμF	$1/10^8$	Thermostatically controlled	Negligible	
Mechanical shock and tilting of mounted crystal	Excessive	$< \pm 2/10^7$	Unlikely to occur in practice	Negligible	

and an output from this crystal is subdivided to give a frequency suitable for land-line transmission. This reference frequency is then transmitted by land line to the London National and Scottish National transmitters, where by multiplying apparatus it is reconverted to 1 149 kc./sec. and is available for direct comparison with the local carriers. At Brookmans Park, for example, an output from the local crystal is combined with the incoming reference frequency; the resultant beats are automatically recorded, and the frequency difference between the two drives may be observed directly from the chart record.

The Brookmans Park record for the period 1100 to 2359 G.M.T. on the 18th June, 1938, has been analysed and the results are given. It should be pointed out that during the period of test no adjustments were made to the crystal. The frequency difference in parts in 10^8 between the two drives have been plotted at 5-minute intervals, except for short periods when the record was marred by line disturbances (see Fig. 13). An additional analysis showing the frequency difference at intervals of 25 seconds over a 10-minute period is given in Fig. 14.

From Fig. 13 it will be observed that for periods of one hour or more the frequency difference was negligible, i.e. less than 1 part in 10^8, and that the total separation was only 6 parts in 10^8. These results indicate clearly that it is practicable to achieve the required frequency stability for common-wave broadcasting by the use of rigid oscillators.

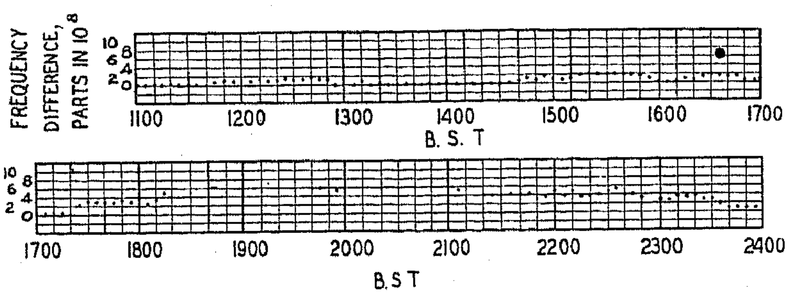


Fig. 13.—Frequency difference between Brookmans Park National transmitter and North National transmitter, 1 149 kc./sec., long-period stability, 18th June, 1938.

Finally, I should like to say a few words about long-distance short-wave telephony, with particular reference to the transatlantic service. While short-wave radio can provide telephone links spanning many thousands of miles at relatively low cost, such circuits are not always effective and free from distortion. Difficulties arise from the nature of the medium responsible for the transmission of these waves. This medium, as is well known, consists of fairly sharply defined regions of high ionization density situated at heights of from 100 to 500 km. above the earth's surface. The layers are subject to variation of height and density which are dependent on the ultra-violet radiation of the sun. Thus, not only is the received field subject to hour-to-hour variations over a wide range but in addition the irregular nature of the transmitting medium gives rise to multiple-path transmission. The multiple-path transmission produces interference at the receiving point between signals which have traversed different ether paths and which have been subjected to different and varying time delays. The time delay between the various components accepted by the receiver is the cause of the distortion and apparently changing audio-frequency response characteristic often noticeable on short-wave circuits.

At times also the medium, as the result of some abnormal activity of the sun, loses its reflecting properties and signals may fall to values so low as to be useless or may even disappear for days. These disturbances, when they occur, generally affect all short-wave radio circuits simultaneously, but they are usually more severe and more prolonged over routes passing near the polar regions. The transatlantic service is particularly liable to such troubles, which are all the more serious in this case because it is the busiest long-distance service in the world. Correlation has been established between times of maximum disturbance of the radio circuits and maximum sunspot activity, and the actual disturbances are accompanied by magnetic storms. The next sunspot maximum is due to occur in the years 1939–40, and for the last few years the possibility of limiting the effects of that anticipated disturbed period has been studied by the American Telephone and Telegraph Co. and the Post Office. The previous bad period occurred when short-wave telephony was only commencing and the main load was carried by the long-wave circuit, which is unaffected by magnetic storms. Now, however, the main traffic is carried by the four short-wave circuits, and the long-wave circuit does not afford an adequate standby.

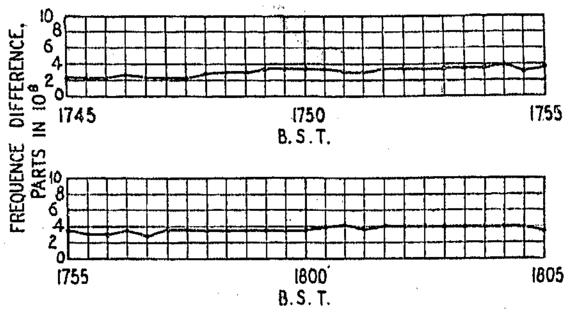


Fig. 14.—Frequency difference between Brookmans Park National transmitter and North National transmitter, 1 149 kc./sec., short-period stability, 18th June, 1938.

In order to reduce as far as possible the deterioration produced by periods of magnetic storm two improvements are necessary, viz.

(1) To increase the received field strength so that it remains above the level of noise by the largest possible margin, in order to reduce as far as possible the extent and duration of fades.

(2) To minimize by some means the effect of wave interference.

As regards (1), the transmitter power at present in use is already approaching the economic limit, and antenna directivity of the fixed type has probably been exploited to the greatest useful extent. The solution has therefore been sought in the use of a single-sideband system of transmission. With regard to (2), until recently there has seemed to be no escape from wave interference, but recent work in America suggests that these effects may be alleviated by the use of a receiving system which is capable of separating the various rays arriving at different angles to the horizontal, and using these as separate factors for diversity reception. This system has been proposed by engineers of the Bell Laboratories and designated the M.U.S.A. system (Multiple Unit Steerable Antenna). Receiving systems of this type for use on the Transatlantic Telephone Service are at present under construction in England and America.

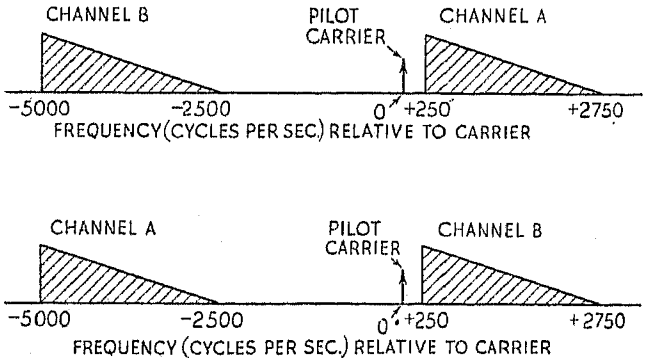


Fig. 15.—Frequency spectra radiated by dual-channel single-sideband transmitter.

The advantages of single-sideband working on short waves were touched on by Dr. R. Bown in his recent Lecture[*] before this Section, when he mentioned that, in addition to the saving in carrier power and the reduction in noise due to the reduced band width required, there was also an improvement in quality due to reduced distortion. The gains due to carrier reduction and lessened band width can be readily assessed as being equal to 6 db. and 3 db. respectively. The gain due to lessened distortion cannot be so readily assessed, but the total improvement in signal/noise ratio due to the use of single sideband for a given peak power at the transmitter may be taken as equivalent to from 9 to 12 db. (in other words equal to raising the transmitted power from 8 to 16 times) over the double-sideband system.

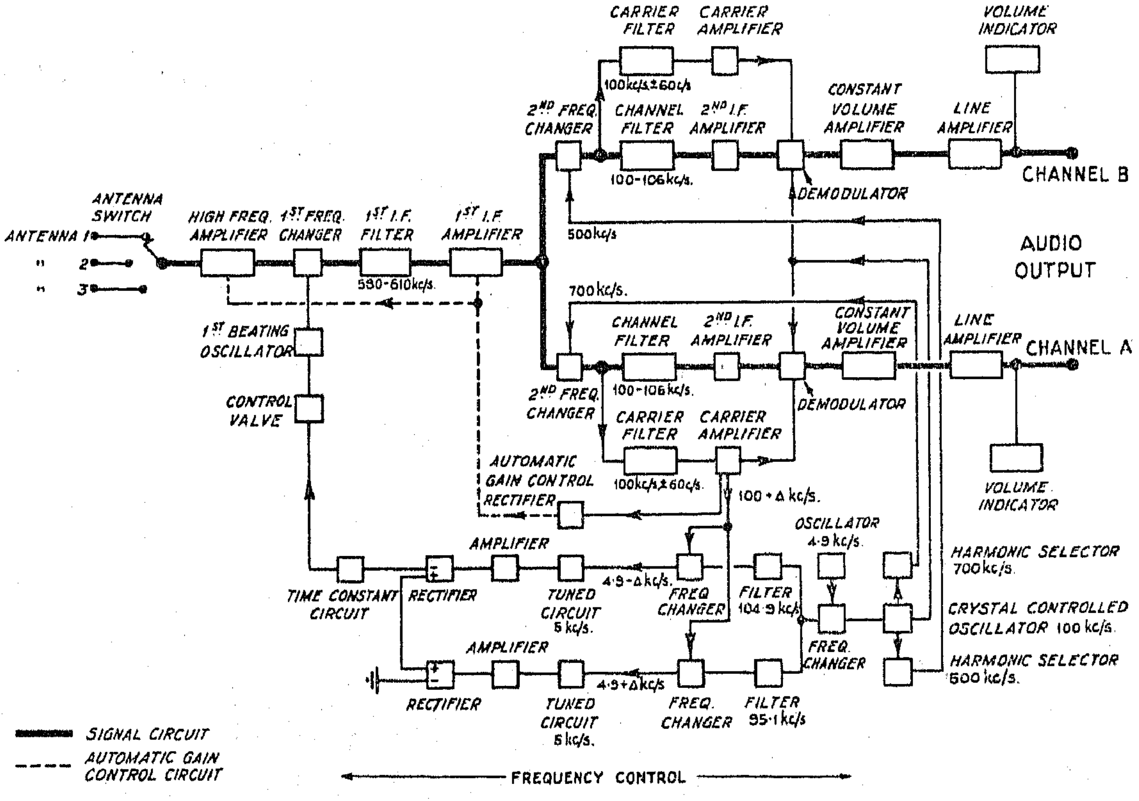


Fig. 17.—Block schematic of dual-channel single-sideband receiver.

The saving in the width of the frequency band occupied by a single channel makes it possible to place two speech channels in a frequency allocation which has previously carried only one double-sideband channel. The extra speech channel is obtained at appreciably less cost than is involved in setting up an additional double-sideband transmitter and receiver. Double-channel working has been in operation experimentally on the London-New York circuit, and it may be of interest to give a brief description of the receiver used by the Post Office—the American Telephone and Telegraph Co.'s receiver has already been described.

Fig. 15 shows a frequency spectrum for the dual-channel transmission. By arranging that there is a separation of at least 2·75 kc./sec. between the channels the intermodulation products of the highest level fall in this range and so do not contribute to the channel-to-channel cross-talk. The possibility of using this vacant band for a telephone channel for service communication on lower modulation has been considered, but equipment for this purpose has not yet been fitted.

The layout of the receiver is shown in Fig. 16 (see Plates 6 and 7), and a block schematic diagram of the arrangements is given in Fig. 17. The receiver incorporates two frequency-change steps; the first intermediate-frequency band is from 594 to 606 kc./sec., and the second intermediate band is 100 to 106 kc./sec. The relatively high first intermediate frequency allows a discrimination of more than 70 db. to be obtained against the image channel approximately 1 200 kc./sec. away, while the relatively low second intermediate frequency allows a discrimination of more than 90 db. to be obtained against the adjacent channel. The frequency of the first beating oscillator in the receiver is electrically controlled, so that the frequency of the pilot carrier at the second intermediate frequency does not differ from that of a 100-kc./sec. crystal-controlled local oscillator by more than 10 cycles per sec. The frequency-control system is non-mechanical in character, the frequency of the first beating oscillator being made to depend on the direct voltage applied to the suppressor grid of a high-frequency pentode control valve. The direct voltage is derived after rectification and smoothing from two low-frequency control tones, nominally at 4·9 kc./sec., which are made to diverge in frequency and amplitude as the reconditioned carriers depart from equality of frequency with the 100 kc./sec. crystal-controlled local oscillator.

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[*] *Journal I.E.E.*, 1938, vol. 83, p. 395.

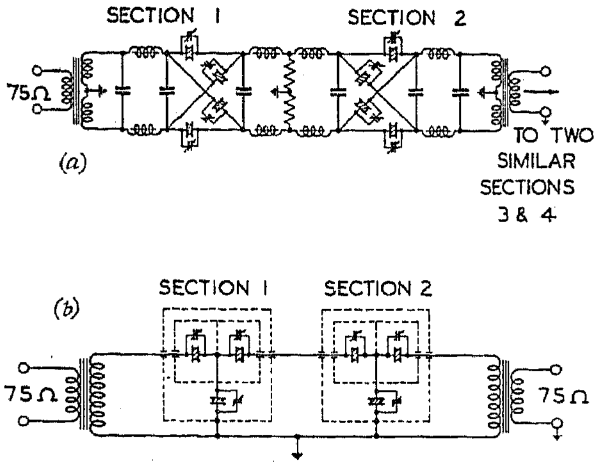
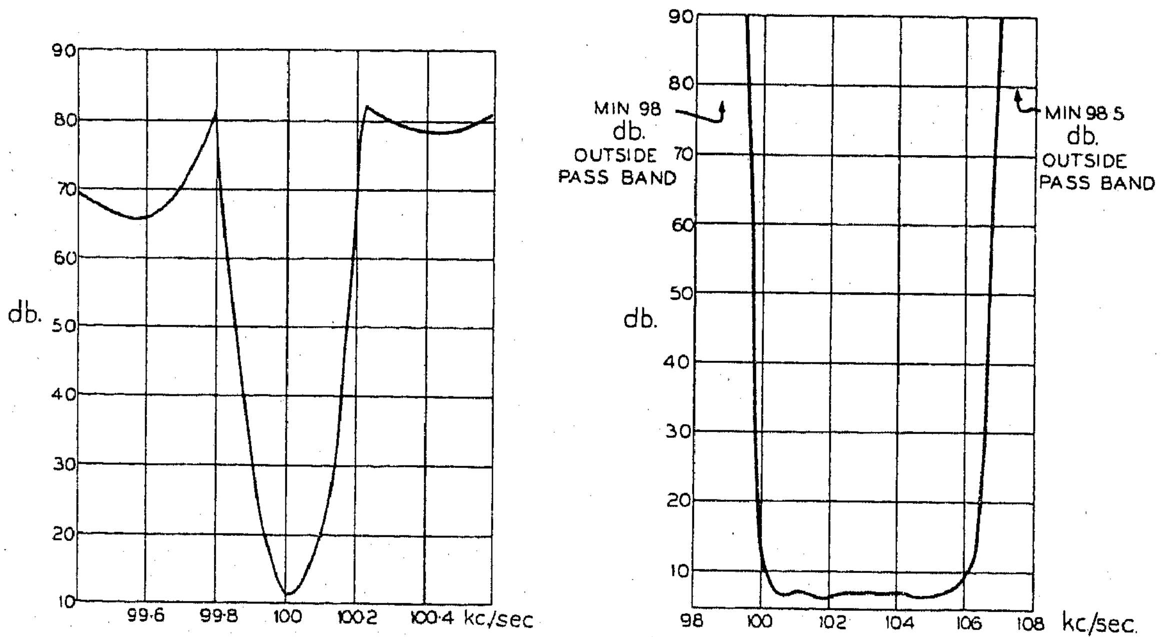


Fig. 18.—Circuit of carrier filter.

The degree of frequency control is such that the locally generated carrier may be used at the detector without any noticeable degradation of speech quality. In practice, however, a reconditioned carrier is generally used.



Insertion loss of carrier filter

Insertion loss of channel filter

Fig. 19

The pilot carrier is selected at the second intermediate frequency by means of a narrow band filter incorporating 6 X-cut quartz plates arranged in two ladder filter sections (Fig 18). The effective band-width of this filter is about 120 cycles per sec. at a frequency of 100 kc./sec. (Fig. 19). By the use of beating-oscillator frequencies of 500 and 700 kc./sec. at the second frequency-changer, similar filters may be used to select the channels. The channel filters have a band-width of from 100 to 106 kc./sec. and incorporate 16 X-cut quartz plates arranged in four lattice sections (Fig. 18). The filters are hermetically sealed, since moisture tends to upset the transmission characteristics. The inductors included with the lattice sections make possible the relatively wide pass-band, while the shunt resistors, together with the balance-to-unbalance transformers joining the two halves of the filter, serve to prevent the transmission of current in phase along the arms of the filter. These longitudinal currents would otherwise impair the high values of attenuation obtained immediately outside the pass band (Fig. 19). Some audio-frequency equalization is incorporated in the receiver to correct for the slight increase in the insertion loss due to the filter near the carrier frequency, so that a music circuit with a band-width of 50 to 6 000 cycles per sec. can be provided when required.

The automatic gain-control system is of the delayed type operating from the pilot carrier. The automatic gain-control voltage operates on two signal-frequency stages and also on two stages of the first intermediate-frequency amplifier. Speech-level variations due to selective fading cannot, however, be completely eliminated by an automatic gain-control system operating solely from the pilot carrier. This difficulty has been overcome by the use of a constant-volume audio amplifier, the gain of which is varied automatically to maintain the speech volume at substantially constant level.

Turning now to the ray-diversity or M.U.S.A. system, a description of the general principle of the experimental system developed and installed at Holmdel, New Jersey, has been given by Dr. Bown.* As already stated, the American Telephone Co. and the British Post Office are each providing commercial systems of this kind for the transatlantic telephone service.

The new system will be much sharper in vertical directivity than the experimental model. The stations are being designed to have the same performance but differ to some extent in details. The British station is being built at Cooling Marshes, near Rochester, Kent, while the American station is being built at Manahawkin, New Jersey.

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* *Journal I.E.E.*, 1938, vol. 83, p. 395.

At Cooling the aerial system will consist of an array of 16 unit antennae placed along the great-circle path between the transmitter and receiver (see Fig. 20). The total length of the array will be approximately 2 miles, with the receiving station located at the end remote from the transmitter. The output from each unit antenna will be conveyed to the receiver by means of a separate buried coaxial transmission line.

It will be obvious from Fig. 20 that if such a system is receiving a wave incident at an angle θ to the horizontal, then if the time of arrival at the receiver of the signal received by the antenna nearest the transmitter is taken as the datum the signal from the next antenna will arrive $\left(\frac{d}{v} - \frac{d\cos\theta}{c}\right)$ seconds earlier and from the the nth antenna $(n - 1)\left(\frac{d}{v} - \frac{d\cos\theta}{c}\right)$ seconds earlier, if d is the spacing between antennae, c the velocity of the wave in space, and v the velocity of the signal on the feeder.

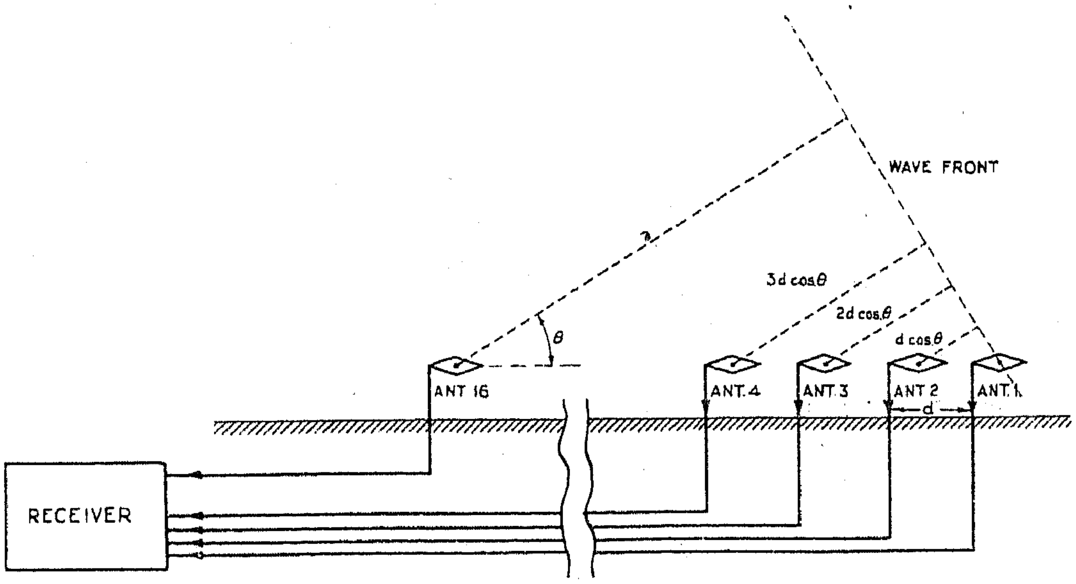

Fig. 20.—Principle of ray-diversity (M.U.S.A.) system.

If delay networks having these values of delay are inserted in the feeders then all signals arriving at a downward angle θ will be in phase at the receiver and if added will produce a maximum resultant equal to their arithmetical sum. Signals arriving at angles other than θ will not be in phase and, if added, will produce a vector sum less than their arithmetical sum. The correction by delay networks for a particular angle of incidence will hold for any frequency. Alternatively the correction can be applied by means of a phase-shifting device inserted in all feeders except the first. The phase shift required in the second feeder will be $\left(\frac{d}{v} - \frac{d\cos\theta}{c}\right) 2\pi f$, where f is the frequency of the signal. Other feeders will require correspondingly larger phase-shifts. Where $\left(\frac{d}{v} - \frac{d\cos\theta}{c}\right) f$ is greater than 1, only the fractional portion need be corrected. As f enters into the expression the correction for a particular angle of incidence will not in this case hold for other frequencies. Both methods of correction would be equally effective. In practice, however, the correction is not inserted in the transmission lines but at a point after the first demodulator, so that the correcting devices operate at a constant intermediate frequency. As a result it is more convenient to use a phase-changer scheme, because of the facility of adjustment of such devices.

It is not essential to apply the phase correction to the signals; it is equally effective to arrange for the appropriate phase-change to be present in the beating oscillator supplies to the demodulators associated with the respective antennae and feeders. In the British receiver this method is adopted and the phase-changes are accomplished in rather a novel way which will be described later.

The vertical polar diagram of an array is given by the product of the response of the unit antenna and the array factor for corresponding wave angles. The unit antenna in the present case is a horizontal rhombic. Such an antenna has a high gain and relatively constant output impedance over a wide range of operating frequencies. By suitable choice of the spacing of the unit antennae it can be arranged that the first major lobe of the polar diagram is caused to move over the range of downcoming wave angles normally met with in practice by a variation of the unit phase-shift of from + 180° to — 180°. The discrimination of the system is high for waves of differing downcoming wave angles which arrive along the great-circle path, but is relatively low for waves of the same downcoming angle which arrive "off course." Fortunately, the waves arrive "on course" for a large proportion of the time and it becomes possible to discriminate between waves of differing downcoming angles to a degree which is adequate in practice. It is possible with a single antenna system to provide more than one set of phase-shifters, so that the antenna system may be phased for optimum reception of more than one ray. These rays will in general correspond to signals which have travelled paths of different lengths. In order that full advantage may be taken of these multiple signals it can be arranged that the audio-frequency signals corresponding to the paths of shorter length are subject to suitable time delays in the receiver (by the use of suitable time-delay networks), so that they may be combined without distortion and with some improvement in the signal/noise ratio of the final output.

The signal/noise ratio advantage of the ray diversity system compared with the unit antenna depends in practice on the polar distribution of the radio noise or static which obtains in a given case. If, however, we assume that the static is negligible and that the major source of noise is the thermal-agitation voltage in the first tuned circuit of the receiver, a 16-element system should present a signal/noise gain of 16 times in power, owing to the combination of the 16 equal signal voltages in phase and the combination of the 16 sets of noise voltages in random phase. That is, the signal increases in power 256 times while the noise increases only 16 times. The improvement in signal/noise ratio is thus $10 \log_{10} 16$, or 12 db. This improvement, added to the improvement due to signal-sideband working, gives a total improvement of from 21 to 24 db. This is based on the assumption that only one branch of the receiver is contributing to the output. Three traffic branches are being fitted to the receiver, and when all three are adjusted to accept three rays arriving at three different angles, then, on the assumption that the three rays are of equal strength, there will be an additional improvement of 10 log 3 or 5 db. This condition will not obtain generally, as the three rays will vary in strength and the output from one branch will usually predominate at a particular time. Nevertheless, the presence of the three branches of the diversity system will reduce the number of fades in a given time, and will thus effect an improvement equivalent to a gain of this order. Thus the total improvement to be expected by a system of this kind compared with a double-sideband transmitter and single-unit antenna connected to the receiver should be from 26 to 29 db.

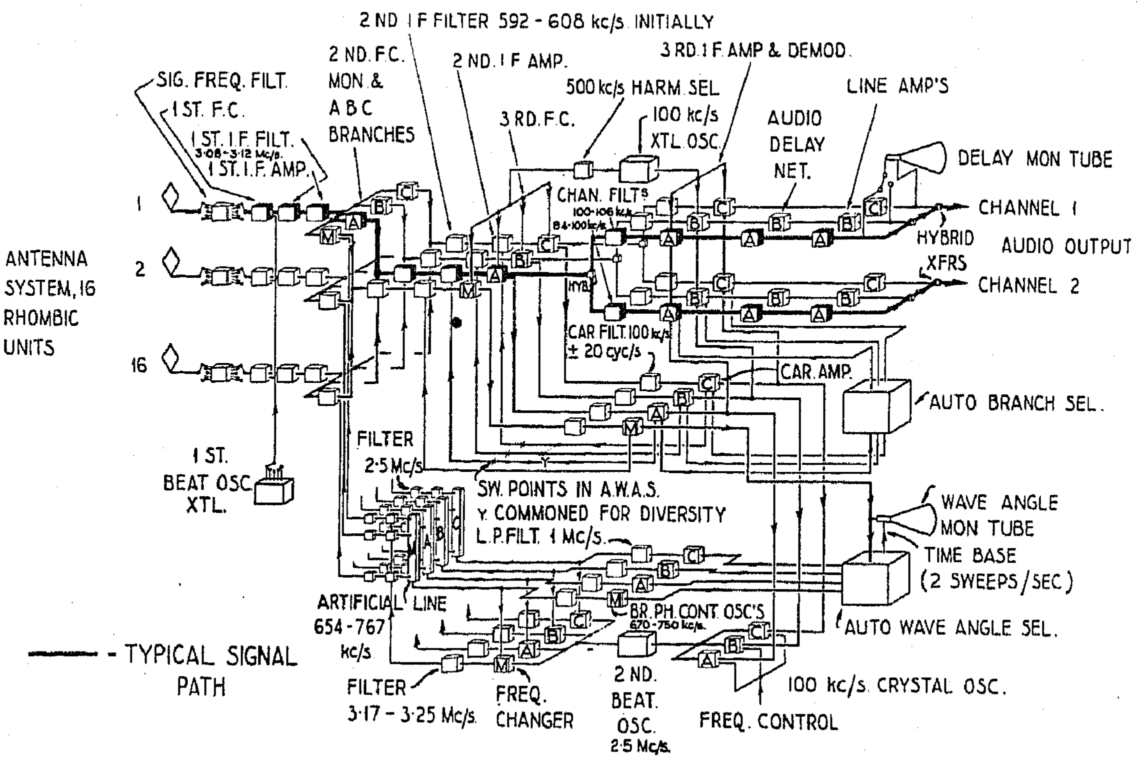

Fig. 21.—Block schematic of British ray-diversity receiver.

The antenna system comprises 16 rhombic antennae, the spacing between centres being 656 ft.

Each unit rhombic antenna is 60 ft. high, the side is 315 ft., and the included angle between the sides is 140°. The impedance of the antenna varies from approximately 850 ohms at 4 Mc./sec. to approximately 625 ohms at 22 Mc./sec. and is balanced to earth. The impedance is matched to the unbalanced coaxial copper-tube transmission line of impedance 70 ohms by a transformer suitable for operation over the range 4–22 Mc./sec. The transmission line consists of a $\frac{5}{8}$ in. diameter internal conductor inside a 2 in. diameter external conductor, and will be filled with dry air under pressure to retard the ingress of moisture. The loss on the longest line is expected not to exceed 6 db. at 20 Mc./sec. The lines are buried in the earth to minimize changes in length due to temperature variations and so to avoid the necessity for expansion joints. A schematic diagram of the British ray-diversity receiver is shown in Fig. 21. Three intermediate frequencies and three frequency-change steps are used. There is no signal-frequency amplification, but adequate protection against the image channel is obtained by the use of 3·1 Mc./sec. as the first intermediate frequency, together with a signal-frequency filter. The other intermediate frequencies are 600 and 100 kc./sec.; the design of this part of the receiver follows that of the single-sideband receiver already described. The receiver is provided with three traffic branches and a monitoring branch so that up to three waves of differing downcoming angles may be received separately and then combined. The purpose of the monitoring branch is to provide visual indication of how many rays are present and their relative strength so that the branch phase controls may be set accordingly either manually or automatically. Initially the receiver is equipped for two speech channels. The first and second intermediate-frequency amplifiers are designed for band-widths of

50 kc./sec. so as to make provision for possible multichannel working.

Each transmission line may feed up to 6 receivers in parallel: when the working frequencies are sufficiently separated no loss of signal/noise ratio occurs. Each receiver is equipped with 5 sets of 16 pre-tuned input circuits, the appropriate set of circuits (each of which consists of two tuned circuits capacitively coupled) is selected and connected to the signal grids of the first frequency-changers by means of ganged switches.

Precautions are taken to maintain equality of phase-shift through the 16 signal and first intermediate-frequency circuits up to the combining point and means are provided to check and adjust this equality. The first tuned circuits are also adjusted to match the 70 ohms impedance of the transmission line to prevent reflection.

The first frequency-changers consist of two hexode valves in which the signal grids are fed in phase while the oscillator grids are fed in antiphase. This arrangement minimizes cross-talk between the pairs of frequency-changers via the common beating oscillator feed.

The first beating oscillator is crystal-controlled and uses low-temperature-coefficient quartz plates in thermostatically controlled ovens. The frequency stability of this oscillator is about ± 3 parts in 10^7. Spare oscillators are provided with an automatic change-over so that they may be put into service in the event of failure of the working oscillator.

A single stage of amplification at 3·1 Mc./sec. is provided, and the inductively coupled tuned circuits used constitute the first intermediate-frequency filter.

The second frequency-changer consists of 4 hexode valves with their signal grids connected in parallel. One of these valves is for the monitor branch and the remaining three for the signal branches. The oscillator grid on each of these frequency-changers is fed with 2·5 Mc./sec. from the appropriate branch phase-changer equipment, and the anodes of the 16 valves belonging to a given branch are connected in parallel. The phase-changer arrangement is shown in Fig. 22. The amount of phase-change produced is under the control of the oscillator O_1 (670 to 750 kc./sec.). This oscillator feeds, via the low-pass filter F1 (1 Mc./sec.), an artificial line L. This line consists of 32 confluent band-pass filter sections of the constant-K type terminated in an M-derived section. Each line unit consists of two filter sections each yielding + 90° to − 90° phase shift for a frequency variation of 670 to 750 kc./sec. The line is tapped at intervals of one line unit to feed a frequency-changer valve FC2. The phase shift between line taps is constant along the line, since the line is terminated in such a manner as to avoid reflection at the termination. The frequency-changers FC2 are also supplied with a frequency in the range 3·17–3·25 Mc./sec. derived from the oscillator O_2 (2·5 Mc./sec.) by modulating it with O_1 (670 to 750 kc./sec.) and selecting the upper sideband with the filter F2 (3·17 to 3·25 Mc./sec.). The frequency-changers FC2 now yield a beat frequency of 2·5 Mc./sec., but each output differs in phase from its neighbours by $\pm\,\phi$, where ϕ can be varied from − 180° to + 180° by varying the frequency of O_1 from 670 to 750 kc./sec.

The phase-control oscillators O_1 are arranged to be controlled in frequency both manually by a variable condenser and electrically by means of a direct voltage applied to a control valve. The advantages of this latter form of phase control lies in its freedom from mechanically variable elements (which is particularly important in the monitor branch), the ease with which it can be adapted to remote control, and its suitability for use in conjunction with a scheme for the automatic selection of the most suitable angles for reception by the traffic branches.*

The monitor branch of the receiver is arranged to sweep over the whole range of unit phase-shift (− 180° to + 180°) at a frequency of about 2 cycles per sec. This is achieved by applying a saw-tooth wave to the control valve of the phase-control oscillator of the monitor branch. This wave is also applied to the X plates of the monitor branch cathode-ray tube. The pattern observed on the fluorescent screen of this tube is a guide to the best setting of the branch phase-shifters. The low rate of sweep—2 cycles per sec.—is determined by the band-width of the carrier filter (40 cycles in this receiver). The monitor cathode-ray tube has therefore to be provided with a fluorescent screen having a slow decay time.

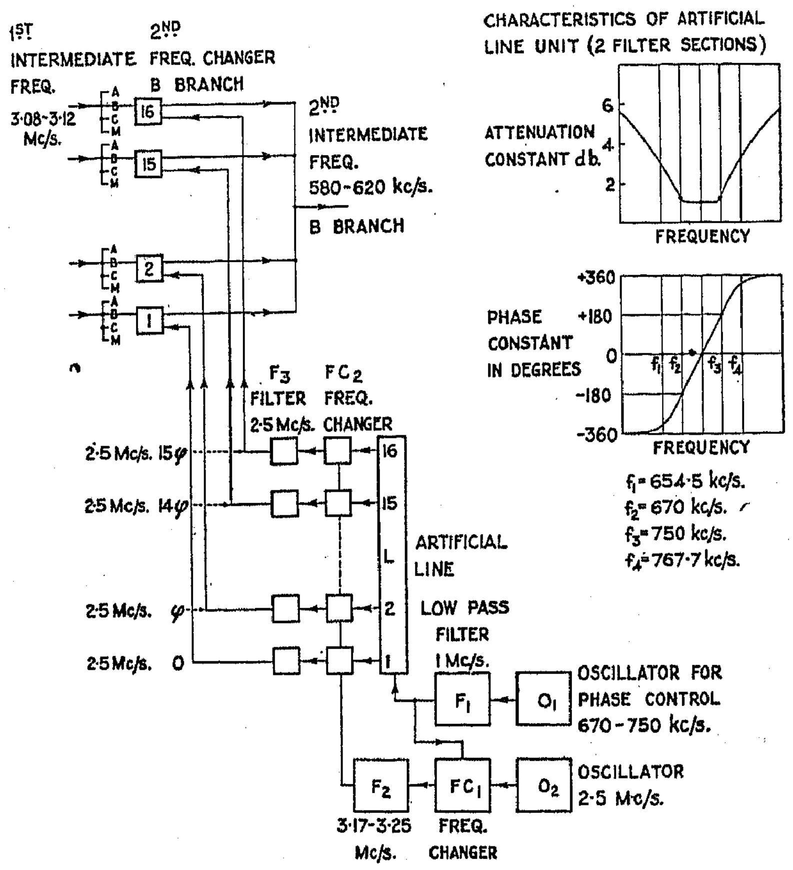

Fig. 22.—Principle of phase-changer.

The frequency-control system of the receiver is identical in principle with that used in the single-sideband receiver already described. The direct control voltages from the three branch frequency-control units feed into a combining circuit to operate on a control valve associated with the second beating oscillator (2·5 Mc./sec.) of the receiver. The latter oscillator constitutes the only tuning control of the receiver and is variable in frequency over a range of about 5 kc./sec. only.

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* It is interesting to note that the above system of phase correction can be used in the case where the receiver is placed at a point along the antenna system instead of at the end. Separate artificial lines, etc., are necessary to deal with space and line delays, however, in order that the difference between these phase shifts may be taken in the case of the forward aerials and the sum taken in the case of the rearward aerials.

The automatic gain-control system, as in the single-sideband receiver, is of the delayed type operating from the pilot carrier. The control voltage is applied to two stages in the second intermediate-frequency amplifier. Provision is made for accurately tracking the variation of gain with control voltage in the three signal branch second intermediate-frequency amplifiers. This is necessary since normally the three branches operate with a common automatic gain control so that the signal of highest level contributes most to the audio output of the receiver.

The system of automatic angle selection favoured for adoption is one in which the branch phase-control oscillators are set automatically to the frequencies corresponding to the angle of the strongest incoming rays. If less than three waves of suitable level are present the selector will disconnect the unphased branches so that they do not contribute noise to the receiver output. When a wave ceases to appear above a certain level the branch which was phased for that ray is released and made available for phasing for any other ray which may appear or be present. Provision is also made for automatic branch selection whereby the branch carrying the strongest signal (as determined by the level of carrier in that branch) supplies the receiver output to the exclusion of the other two branches. This scheme is an alternative to combination with delay correction. The signal/noise advantage of combination with delay correction is slight unless the three branches yield signals of very nearly equal signal/noise ratios.

For delay correction audio delay up to 2·97 millisec. is provided in 9 steps of 300 microsec. together with 9 steps of 30 microsec. The delay networks are brought into circuit by the operation of relays; the relays are at present brought into action by a manually operated switch, but automatic correction may be fitted later.

By grading the contribution of each antenna to the combined output it is possible to reduce the size of the minor lobes of the polar diagram of the antenna system compared with the major lobe. This advantage is obtained at the expense of array gain, however. The increased discrimination offered by the scheme may be of advantage when the incoming bunch of rays consists of two or more components of slightly different downcoming angles but of different path lengths. Tapering in this receiver can be effected by adjustment of the gains of the 16 first intermediate amplifier stages by grid-bias control; grading may thus be introduced at will by operating a single switch.

The initial equipment at Cooling will consist of two receivers, each suitable for two speech channels. The equipment is mounted on standard 19-in. racks and for the two receivers consists of 88 bays. The total length of the receivers will therefore be about 110 ft. with an average height of about 8 ft. and the number of valves in use will be 1 079 for the two receivers. This seems a lot of equipment, but when it is realized that these receivers will give an improvement of about 1 000 over a simple receiver the complication becomes worth while.

It is of course obvious that any given improvement in a radio circuit can be obtained by increasing the power radiated by the transmitter or by increasing, within limits, the directivity of the transmitting or receiving aerials, and the decision as to where the improvement is to be obtained usually depends on the relative costs. In other words, one has to decide where a given number of decibels improvement can be obtained most cheaply.

For example, an improvement of 3 db. could be obtained by doubling the power of the transmitter, involving a cost of, say, £10 000. It might be possible, however, to get this 3 db. gain by doubling the size of the receiving antenna at a cost of, say, £1 000. Radio engineers have realized that for true economy of plant on a fixed radio service the cost of the receiver should approximate to that of the transmitter. Hitherto it has usually been cheaper to obtain improvements at the receiving end, as the total cost of the receiving equipment was generally much less than the cost of the transmitter. Now, however, the cost of the receiver has reached the same order as that of the transmitter, and if further transmission improvements become necessary in the future it seems probable that they will have to be obtained at the transmitting end.

In conclusion I should like to express my thanks to Mr. H. G. Beer and other colleagues in the Radio Laboratories for the great assistance I have received in the preparation of information for this address.

I must also acknowledge my indebtedness to the British Broadcasting Corporation for the data relating to the performance of the common-wave broadcasting transmitters.

THE 50-kW X-RAY GENERATOR AT THE DAVY-FARADAY LABORATORY OF THE ROYAL INSTITUTION*

By ALEX MÜLLER, Ph.D., and R. E. CLAY, M.Sc.†

(*Paper first received* 22*nd June, and in final form* 18*th July*, 1938.)

SUMMARY

The X-ray tube described has been specially built for crystal-structure analysis. A short theoretical discussion of the limits set to the power of an X-ray generator is followed by a detailed description of the machine and of the rectifier system which feeds it with high-tension current.

INTRODUCTION

The early work on crystal-structure analysis which followed Prof. Max von Laue's discovery of the diffraction of X-rays by the regularly-arranged atomic scattering centres in a crystal was carried out with apparatus designed essentially for medical work. It was soon realized, however, that X-rays of longer wavelength, generated at lower voltages, were more convenient, and special tubes were made for crystal-structure analysis. For most purposes a wavelength between 1 and 2·5 Å. is suitable; this range includes the characteristic radiations from copper, iron, nickel, and chromium, and requires voltages from 20 to 30 kV.

Progress in crystal-structure analysis rendered an increase in intensity of the X-rays desirable; this can only be obtained by increasing the electrical power fed into the X-ray generator. Moreover, in order to obtain sharp spots on the photographs which can be measured accurately, the X-rays incident on the specimen must be confined to a narrow pencil, and it is essential, if full use is to be made of the electrical power fed into the tube, that the origin of the X-rays (which is the focus of the cathode stream within the tube) be comparable in size with the cross-section of this pencil.

LIMITS TO POWER INPUT

Of the electrical energy fed into an X-ray tube about one part in a thousand is converted into X-rays; the rest appears as heat, which is developed in the focus of the cathode stream, and is dispersed by thermal conduction through the metal of which the target is made, and in most cases is finally removed by flowing water. The temperature of the target within the focus rises as the electrical power fed into the tube is increased, and a limit is set by the melting point of the metal; for a focus 1 mm. in diameter on a copper target this limit is about 1 kW. If, in place of a circular focus, a line focus 1 cm. long and 1 mm. wide is used, the limit becomes 3·6 kW.

A very considerable increase in the limit of power input, with a resultant increase in the intrinsic intensity of the X-rays, is obtained if the surface of the target is in motion. In the machine described in this paper the focus is formed on the flat face and near the circumference of a large hollow wheel rotating at high speed and cooled from the inside by circulation of water. In this way, while the focus is stationary in relation to the casing of the machine, the heat is distributed over a circular band on the surface of the wheel.

A factor of 10 is introduced into each of the examples given above if the surface of the target is moving at 2 000 cm. per sec., a speed easily attained, for example, by the periphery of a wheel 15 cm. in diameter running at 2 500 r.p.m.

A mathematical analysis of this problem,‡ taking into account the effect of the repeated heating as the wheel rotates, leads to the following formula:—

$$P = \frac{4{\cdot}18 \times 1{\cdot}43k(T - T_0)l\sqrt{\left(\frac{\rho c w v}{k}\right)}}{1\,000\left[1 + \frac{1{\cdot}43}{2\pi^2}\frac{l}{R}\left(1 + 2{\cdot}30\log 8\frac{R}{l}\right)\sqrt{\left(\frac{\rho c w v}{k}\right)}\right]}$$

where

P = input limit, in kilowatts;
T = maximum temperature in the focus }
T_0 = temperature of the cooled surface } in degrees Centigrade;
w = width of the focus }
l = length of the focus } the direction of l being along a radius of the wheel;
R = average radius of the circle described by the focus on the surface of the wheel;
v = velocity of the focus, in cm. per sec.;
ρ = density of the target, in grammes per cm^3;
k = thermal conductivity of the target metal; and
c = specific heat of the target metal.

The formula only holds for values of the velocity which make the number under the square root large compared with unity.

This formula forms the basis of the design of the machine. If figures are inserted to correspond with the dimensions, a limit of 46 kW is obtained; the machine will take 50 kW without showing signs of deterioration of the target. This excess over the calculated value is due to the finite thickness of the target, which produces a more efficient cooling than that assumed in the calculation.

Since the metal of which the wheel is made and the size of the focus are fixed, the only factors in the formula by which an increase in the input limit can be obtained are the size of the wheel and its speed; if the speed of the wheel in the present machine were increased to the breaking point, the input limit would be raised 16 %. If the diameter of the wheel were doubled while the speed remained the same, the limit would be raised 65 %. A very considerable increase would be obtained if the material of the target were changed from steel to copper. This is essentially due to the much higher thermal conductivity of copper. For the same dimensions and the same speed the limit would be raised about 4 times, allowing thus an input of the order of 200 kW. Although it is unlikely that the water-cooling in the present machine could be raised to cope with this increase, the change from steel to copper would allow a sharper focusing at the input of 50 kW.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Davy-Faraday Laboratory of the Royal Institution.

‡ *Proceedings of the Royal Society*, A, 1927, vol. 117, p. 30; 1929, vol. 125, p. 507; and 1931, vol. 132, p. 646.

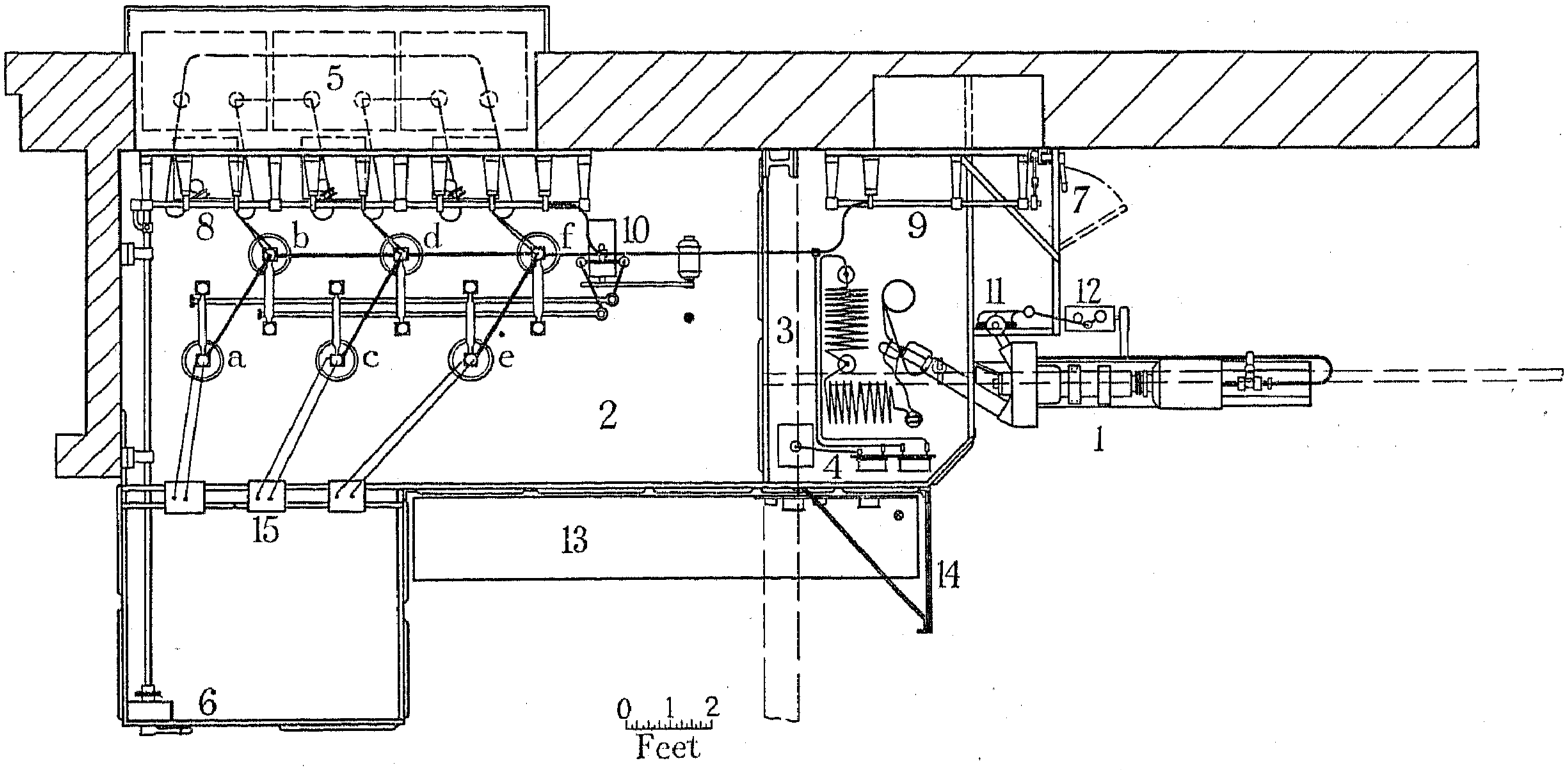

Fig. 1

The great increase in the current density in the cathode stream raises the question whether a saturation of X-ray production might be reached. Such an effect would occur if the interval between successive impacts between an electron and any atom were comparable with the time of relaxation of the atom. With a current of 1·5 amp. passing through a focus of 0·5 cm. area, an atom is made to emit X-rays about 300 times a second, whereas the relaxation time is 10^{-10} sec.*

Measurements of the X-ray intensity made with the present machine show that the intensity is proportional to the input power, provided that the voltage is above the critical excitation voltage for the metal of the target.

DESCRIPTION OF THE MACHINE

General Layout of the Plant

Before giving a detailed description of the various parts of the machine and the rectifier, it may be well to give in broad outline the general arrangement and to indicate the space which it occupies and the demands which it makes on the public supplies.

In the plan drawing (Fig. 1) the X-ray machine is shown at (1); it is mounted on the bed of an old lathe which is bolted down on to a concrete foundation, and a travelling gantry is fixed to the ceiling above it for ease in handling the parts. The rectifier feeding current to the machine is shown at (2), and the three main high-voltage transformers at (5); these stand in an opening in the wall which is closed on the outside by metal screens which are earthed for safety and can be removed so as to allow the transformers to be run out on rollers into the passage-way for inspection.

The rectifier and the high-voltage terminal of the machine are protected by an enclosure of expanded metal, to which entry can be gained only through gates. These are interlocked electrically with the main contactor, so that the high voltage is switched off by the first movement of either gate, (6) or (7). In addition to this, further movement of the handle operates a switch and earths all high-voltage terminals before the gate is released. These earthing switches are shown in Fig. 1 at (8) and (9).

The X-ray machine and the transformers weigh nearly 1 ton each, and on this account a basement laboratory 40 ft. by 20 ft. has been set aside for this plant, which is arranged along one of the long sides of the room.

The main supply is derived from the 400-volt 3-phase mains, from which up to 70 amp. on each phase is drawn. A single-phase auto-transformer feeds the pump heaters and the filament of the machine (this draws about 30 amp. at 230 volts). The main motor driving the machine takes up to 20 amp. from the 200-volt d.c. main, and a further 10 amp. from this supply is used for small pump motors. All relays and the main contactor are operated on 20 volts (d.c.), derived from a battery, and take altogether about 10 amp.

The demand on the water supply is heavy; the machine takes, when running at full power, about 25 litres per minute, with a rise in temperature of about 30 deg. C. A further 10 litres per minute is used for cooling the valves and pumps.

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* W. Wien and F. Harms: "Handbook of Experimental Physics" (Akademische Verlagsgesellschaft M.B.H., Leipzig).

All wiring is done in steel conduit placed in floor ducts, and all the auxiliary apparatus such as relays, auto-transformers, and fuse-boxes is mounted under a bench, shown at (13) in Fig. 1, at one end of which are arranged the controls and measuring instruments. A screen (14), of lead in the lower part and of thick plate-glass in the upper part, protects the operator from stray X-rays.

The Target

A cross-section of the assembled machine is shown in Fig. 2. The target is a hollow wheel built up of two parts, (5) and (8), which are screwed together and welded.

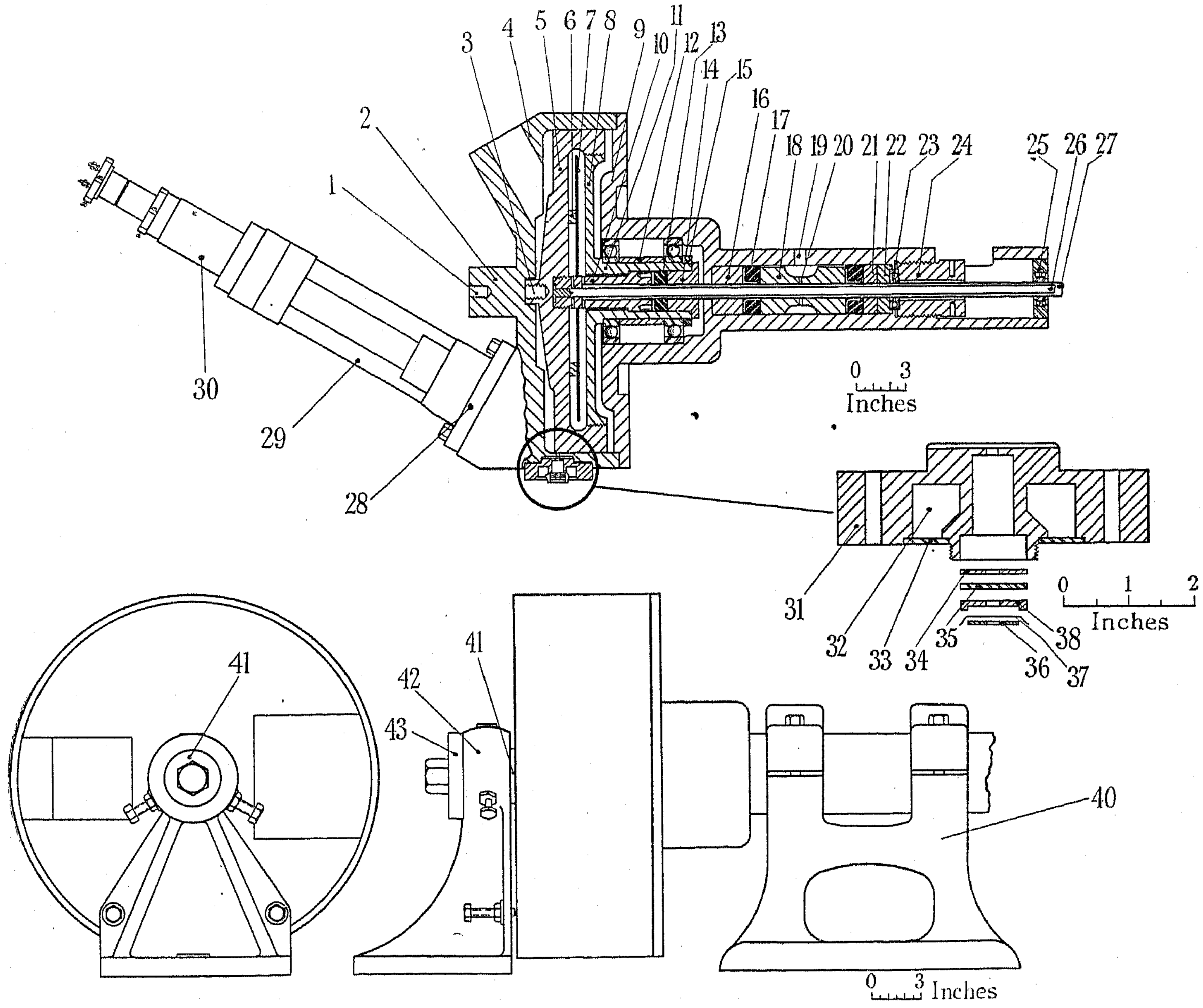

Fig. 2

The cathode rays impinge on the flat portion of (5) in a line focus 3 cm. long and 1 or 2 mm. wide, lying along a radius so as to distribute the heat over as wide a band on the surface as possible. The wheel is mounted in the case so that this flat surface is opposite the window through which the X-rays emerge.

The wheel runs on ball bearings the inner races of which are clamped to a cylindrical portion (11) by the screwed ring (15) and the distance-piece (12).

The driving shaft (27) is a steel tube 1 in. diameter, hard-soldered into a plug (14) which fits into the end of the cylindrical part (11), and is arranged so that when the six bolts tightened the rubber ring (13) is compressed and seals the joint. Water is fed in through an inner tube (26) and passes radially outwards inside the wheel, over the edge of the baffle plate (7), and inwards again to the centre, whence it escapes through the annular space between the inner and outer tubes.

Great care was taken in making the wheel, which is 20 in. diameter and weighs 2 cwt., so that it should be accurately balanced and free from vibration when running at 2 000 r.p.m. This wheel is made of steel and, of course, gives iron X-radiation; for some purposes the radiation from other metals is required, and it is hoped, in the future, to make other wheels, possibly of copper, which can be plated with silver, chromium, or nickel.

A screwed hole (3) is provided into which the end of a long bolt may be screwed; by this means the wheel can be withdrawn from its position in the case for inspection of the ball bearings.

The Case

The case is made in two parts, (2) and (9) in Fig. 2; they are separately supported on castings which fit and slide along the bed of an old lathe. They fit together with a simple flange joint which is made vacuum-tight by simply "wiping" it with Apiezon sealing compound Q. The ball bearings in which the wheel runs fit into a recess in (9), while the shaft passes out through the special stuffing-box to be described later. A fitting (28) is bolted to a projection on (2) with a rubber gasket to make the joint vacuum-tight; this carries the glass insulating tube (29) to which is fitted at its far end the cathode (30), to be described in detail later. In order to throw the focus as near to the edge of the wheel as possible, the cathode is mounted at an angle of 60°.

A vacuum of about 10^{-4} mm. of mercury is maintained within the case, in spite of small leaks through the stuffing, by a battery of three oil diffusion pumps in parallel backed by a smaller oil diffusion pump, backed in turn by a large-capacity, two-stage, rotary oil pump. These are shown in the general layout diagram (Fig. 1) at (11) and (12).

A manifold of welded steel tubes is bolted on to the projection (4), shown in Fig. 2, and the pumps are coupled to this with rubber sleeves. Provision is made in the manifold for freezing out oil vapour with solid carbon-dioxide or liquid air, but this has proved to be unnecessary.

Mounting

The machine is mounted on the bed of an old lathe; castings were made to support the two parts of the case, a 5-h.p. d.c. motor which drives the wheel, and a small fitting through which water is fed into the inner tube of the shaft and carried away to waste from holes in the outer tube. The casting which supports (9) has two **V**'s in which rests the cylindrical portion housing the stuffing; it is held securely in place by clamps bolted to the tops of the **V**'s.

The other part of the case, (2), is supported so that it can be adjusted accurately to alignment with (9). A boss (41) rests on two screws which pass through the ring-shaped head of the casting (42); two more screws passing horizontally through the lower part of the casting bear against the vertical flat face of (2), while a ball-headed bolt screwed axially into the boss (41) bears in a conical hole in a flat plate (43), which slides on the rim of the ring-shaped head of the casting. One degree of freedom, an axial rotation, is left, but this is eliminated by the mounting of the pumps.

The Stuffing Box

A vacuum-tight seal with the rotating shaft is made with standard 1-in. hat leathers compressed on to the shaft by rubber rings (17), which are moulded to fit the hat leathers and also the inside of the stuffing box. There are two of these leathers, and the space between them is exhausted by an auxiliary pump through the side tube (19). The leathers are evacuated under molten vaseline so as to expel all air and to provide a certain amount of lubrication, though this has recently been augmented by an oil drip-feed on to a piece of wick mounted inside the distance-piece (18), which is in contact with both leathers. The shaft is worn into grooves by the leathers, but its life can be prolonged by altering the distance-pieces (16), (18), and (21) so that the leathers are moved on to a fresh part of the shaft from time to time. Both parts of the stuffing are compressed by the large screw (24), the thrust from which is transmitted through a ball bearing (23).

The Drive

The wheel is driven by a d.c. motor because it is necessary, when starting, to apply a steady, small torque to the somewhat fragile shaft. Protection of the shaft against excessive torque is provided by a coupling which allows an angular displacement against springs of two parts which is dependent on the torque; this relative movement, if excessive, breaks a contact which normally connects two slip-rings together, and switches off the motor. In addition to this, a relay operated by the armature current breaks the control circuit of the main contactor and switches off the high-voltage supply.

The Window

The material of which the window is made must be selected from the lighter elements, for the absorption coefficient rises very rapidly with the atomic weight. For most purposes a window of lithium, protected on the outside with a piece of thin cellophane, is used, but for some purposes where it is possible to have the slit system defining the beam of X-rays incident on the specimen inside the window, cellophane alone may be used; when this is done, the cellophane is mounted on the end of a narrow tube along which the X-rays pass. It is not possible to place a cellophane window close to the focus of the cathode stream because secondary electrons very soon destroy it.

An enlarged view of the composite lithium-cellophane window is shown in Fig. 2. The steel, water-cooled fitting (31) bolts into a recess in the case of the machine, the joint being made vacuum-tight with a rubber gasket; this has a hole through it which is small at the inner end, so as to limit as much as possible the bombardment by secondary cathode rays, and opens out to a recess in front into which fit in succession a brass washer (34), the lithium (35), and a second brass washer (38). Upon this second washer is mounted the cellophane (37). A smaller washer fits loosely into a recess in the larger, they are both warmed and coated with a layer of soft wax, then a piece of cellophane is placed over the larger washer and the smaller one is pressed into the recess. The outer washer is then made tight with the rim of the recess in the steel fitting with Apiezon sealing compound Q.

The Cathode

The most favourable conditions for the production of a focus 3 cm. long and 1 mm. wide had to be found entirely by experiments. These were done first with comparatively large currents and low voltage in a special apparatus, then in a 5-kW generator built on the same lines, and finally with the present machine. In Fig. 3 a longitudinal section of the cathode is shown; the section is horizontal in the lower part of the diagram so as to show the filament, and vertical in the upper part so as to show the supporting eyelet (12).

A filament (43) of 0·8-mm. tungsten wire wound in 25 turns on a mandrel 1·27 mm. in diameter is mounted with small wedges in the supports (41) and (46). A cap (40) fitting into the end of the tube (30) is closed at the front by a flat plate having in it a slot 4 cm. long and 5 mm. wide. The filament is adjusted so that it is parallel with the slot and about 3 mm. behind the front edge of the slot; this distance can be adjusted by altering the distance-pieces (21), the effect being to alter the width of the focus—the farther forward the filament, the wider the focus. The front face of the end cover (40) is parallel with the face of the target and about 1 cm. from it, this distance being adjustable by altering the distance-pieces (19). The filament support (46) screws into the plug (39), which fits the end of the tube (31); the other support (41) screws into the part (42), which has a conical portion fitting into a conical hole in the plug (39). Mica is placed between the two conical surfaces, which are held firmly together by the screwed rod (33); at its far end this rod screws into the water-cooled part (25).

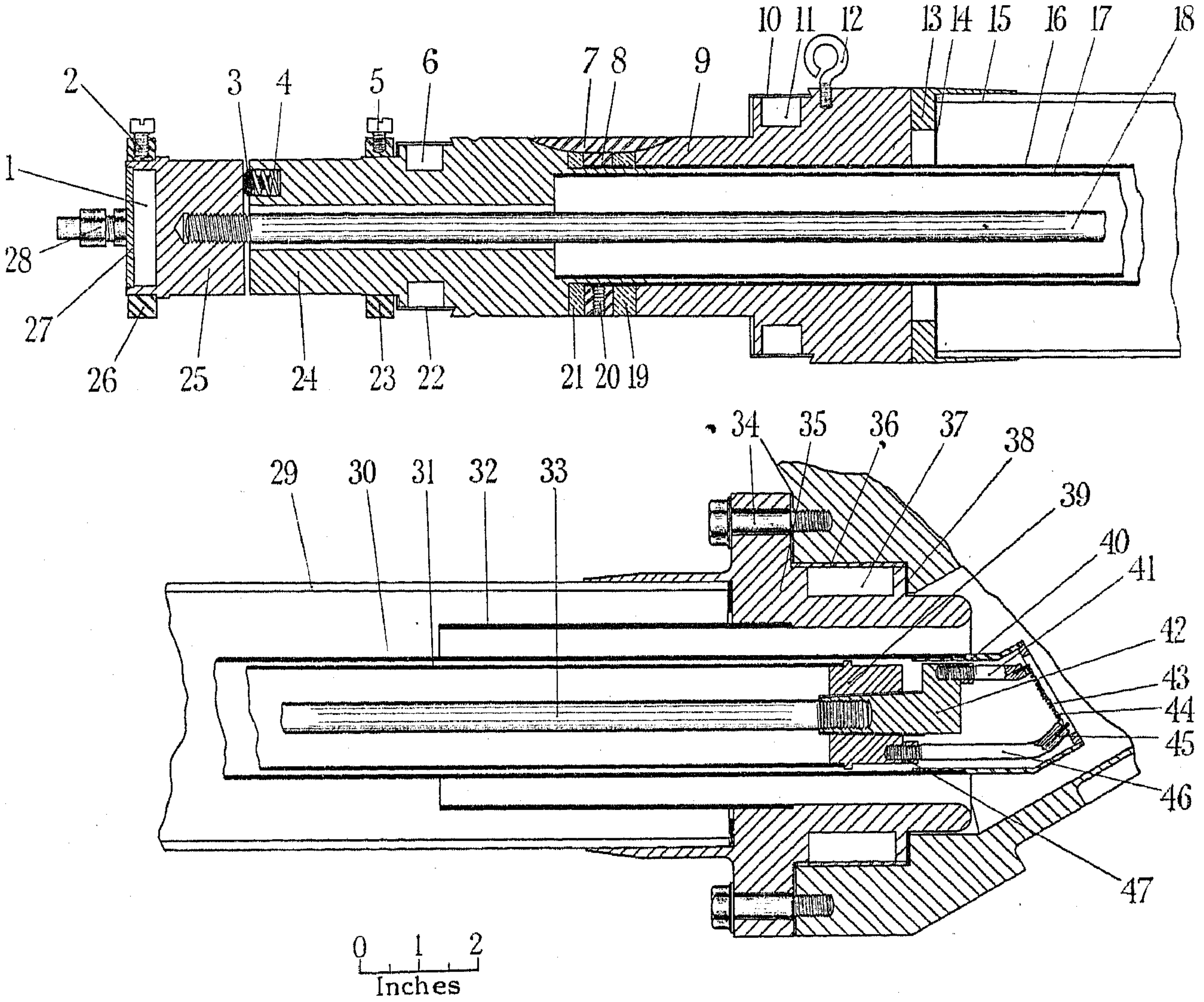

Fig. 3

The main supporting tube, labelled (30) in the lower part of the diagram and (16) in the upper part, is a sliding fit in the water-cooled part (9), and the ring (8) clamped to the end of the tube bears against the distance-pieces (19). The inner tube, (31) and (17), fits into the water-cooled part (24); three spring-loaded fibre buttons working in holes in the end of (24) press against (25) and keep the rod (33) under tension. A key (7) prevents rotation of the parts, and all the joints are made vacuum-tight with sleeves of rubber bicycle tubing.

The fitting (35), which bolts on to the case of the machine, is shown in section in Fig. 3. The joint is made with a rubber ring at (38), water-cooling is provided at (37), and a thin-walled extension embraces the end of the glass insulating tube (29); this joint being made with a rubber sleeve. A steel sleeve (32), supported from the fitting (35), removes electrical stress from the glass at the sharp edge of (35).

The weight of the cathode is taken by a rod hooked into the eyelet (12) and into a large porcelain insulator suspended from the ceiling. Electrical connection from the filament-heating transformer is made on to the ring clamps (23) and (26).

The High-Tension D.C. Supply

The working current (up to 2 amp. at 25 to 30 kV) is derived from transformers and a rectifier system. Since X-rays are generated only when the voltage applied to the cathode is above a certain critical value characteristic of the metal of which the target is made—in the present machine, with an iron target, this voltage is about 12 kV—it is advantageous to employ a circuit which gives a d.c. supply with only a small a.c. component. With any single-phase circuit the voltage drops to zero twice in every cycle; the voltage can be maintained with condensers, but when large currents are being drawn the size of the condenser required makes its use impracticable. For this reason a 3-phase circuit has been adopted.

Six valves are used, in three pairs, connected as shown in Fig. 4. It will be seen that the three anodes of valves *b*, *d*, *f* are connected together and to the cathode of the machine X, while the three cathodes of valves *a*, *c*, *e*, are connected together to earth and thence to the target of the machine. The high-voltage terminals of the three transformers are connected either in star or in delta to the three points T_1, T_2, T_3 common to the valves of the three pairs. The circuit is analogous to the bridge circuit employing four valves on single-phase; for comparison a diagram is given in Fig. 5 of this common circuit.

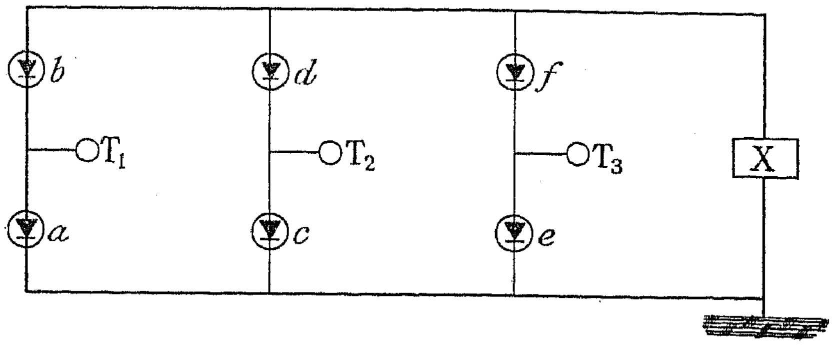

Fig. 4

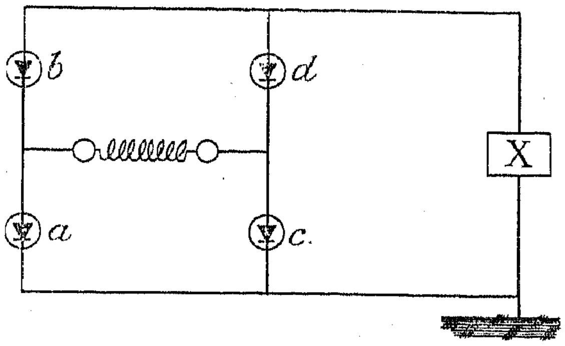

Fig. 5

Each transformer delivers its full sine wave and each valve has to withstand, during its non-conducting period, a back voltage equal to that applied to the machine. The output current is shown for one cycle of the supply in Fig. 6. It will be seen that it falls to about 86 % of the maximum; the r.m.s. value of the output is theoretically 0·956 of the maximum.

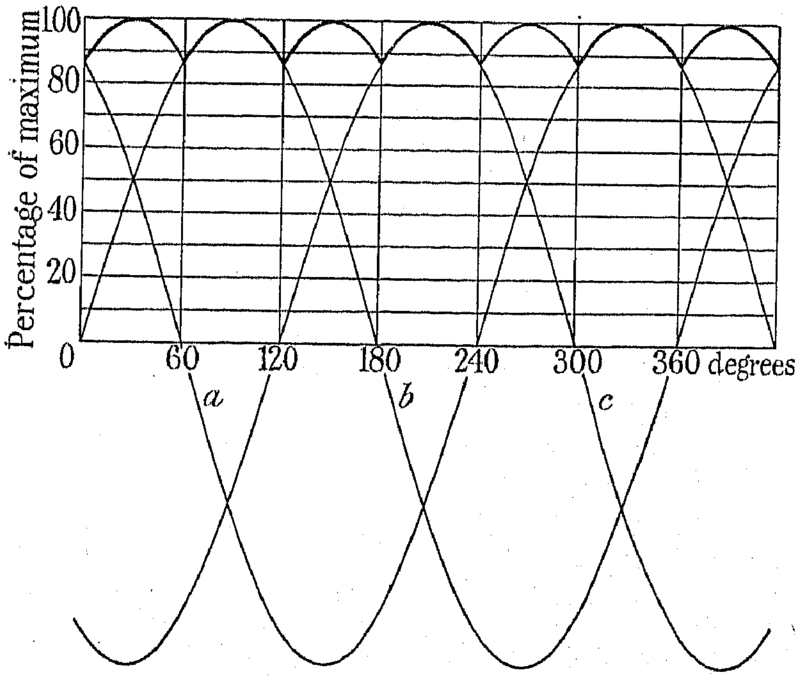

Fig. 6

The change from star to delta connections is readily made by altering a few links. The delta connection allows a current up to 2 000 mA to be drawn at a voltage of 26 kV, while the star connection allows a higher voltage to be used but limits the current to about 1 300 mA.

The secondary winding of each transformer is in two portions, which are normally connected in parallel; by altering links inside the inspection covers it is possible to connect the secondaries in series and thus double the output voltage if this is required for special purposes.

THE VALVES

Mounting and General Arrangement

The six valves are demountable and continuously exhausted, they are all alike and are similarly mounted, each on the top of an insulating paxolin column.

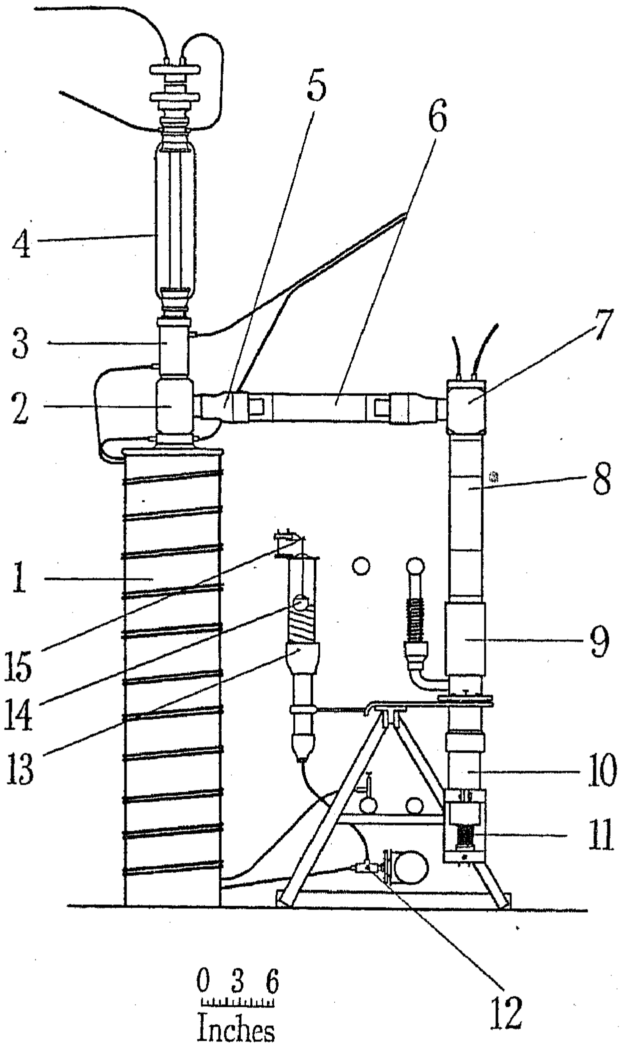

Fig. 7

Fig. 7 shows an elevation of one of the valves. (1) is the paxolin column, (2) is a tee-piece leading to the pump, (3) is the anode, and (4) is a glass insulator supporting the cathode. The glass insulating-tube (6) is jointed to the tee-piece (2) by means of a rubber sleeve and the connecting-piece (5); a similar connection at the other end of (6) leads to the tee-piece (7). From the lower limb of this tee-piece a steel tube (8) leads to the top of the diffusion pump (9); this is heated by a bowl-fire element (11) mounted inside the hollow copper block (10) which forms the lower part of the pump. This method of heating allows for expansion of the wire with which the element is wound, and very seldom gives any trouble. The upper limb of the tee-piece (7) is closed with a steel disc bolted on with a rubber gasket; a coil of copper tube through which water is circulated hangs from this inside the tube (8) so as to condense oil vapour from the pump, which tends to cause a gas discharge in the glass tube (6). The high-pressure sides of the pumps are connected in threes to two backing diffusion pumps which are backed by a rotary 2-stage box pump, shown in Fig. 1 at (10).

The valves are arranged alternately in two rows as shown in Fig. 1, where the lettering corresponds to the circuit diagram (Fig. 4); the six pumps are mounted alternately on opposite sides of a **T**-girder supported on feet between the two rows of valves.

Water-cooling

Water for cooling all parts maintained at high voltage is led through 30-ft. lengths of rubber hose wound on the paxolin columns. It escapes to waste through similar coils, and by means of tee-pieces with a constriction, of which (12) in Fig. 7 is one, causes a rise in level in the fitting (13). A float made of a ping-pong ball (14) closes a contact (15) so that, if the water fails, relays are operated which switch off the filment-heating current, the pump heaters, or the main high-voltage supply.

It will be seen from Fig. 4 that the anodes of valves *a*, *c*, *e*, are connected respectively to the cathodes of valves *b*, *d*, *f*. These parts are accordingly cooled in series through hoses on the supporting columns of valves *a*, *c*, *e*. The cross-connections are made of copper pipes, which serve also as electrical connections; short lengths of rubber hose are inserted where insulation of the filament-heating circuits requires it.

The anodes of valves *b*, *d*, *f*, are all at the same high potential and are cooled in series by water led up a coil of hose on column *b* and down to waste through a similar hose on column *f*. The cathodes of valves *a*, *c*, *e*, are at earth potential and can be water-cooled without the necessity for any insulating hose beyond that required to avoid short-circuits of the filament-heating transformers.

Filament heating

The filament-heating transformers are operated from a 3-phase auto-transformer with tappings so that the voltage applied to the primaries can be adjusted. They transform down to about 6 volts and can deliver up to 170 amp. The three transformers feeding the filaments of valves *b*, *d*, *f*, have the secondaries insulated for the full voltage of the main transformers.

Internal Construction

Fig. 8 is a sectional drawing of one of the valves. The filament system consists of six tungsten wires, each 0·3 mm. diameter and 4 cm. long, arranged in parallel; they are mounted between holes in the two opposed rims (6) and (7), into which they are secured with small wedges. By mounting them between holes which are not on the same generator of the cylindrical surface on which they lie, a curvature can be given to them while at the same time a constant distance is maintained throughout their lengths from the surrounding cylindrical anode; in this way tension due to electrostatic forces is reduced.

The rim (7) is carried on the piece (29), which fits into the end of the supporting tube (12). It has a conical hole in it into which fits the cone at one end of the piece (28), and this carries, on a stem at its other end, the rim (6). A layer of mica separates the two cones, which are held firmly together by the screwed rod (27). At its other end this rod screws into the water-cooled piece (19), while the supporting tube (12) fits into the water-cooled piece (15). Three spring-loaded fibre buttons (18) keep the rod (27) under tension and allow for differential expansion between (27) and (12). The gap between (15) and (19) is bridged with rubber bicycle tubing.

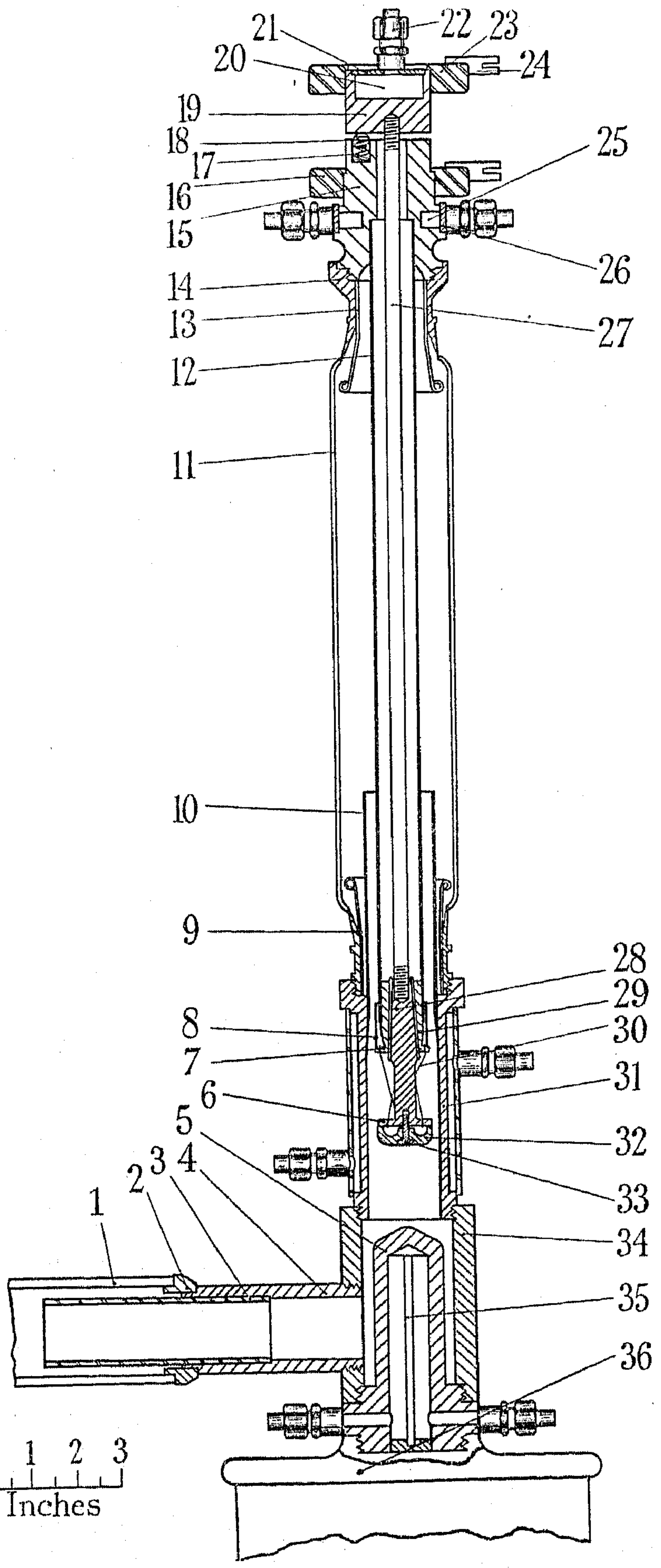

Fig. 8

The piece (15) screws into a copper piece (14) which is sealed to the end of the glass insulating tube (11), the lower end of which is similarly sealed to the copper piece (9). This screws into the anode (31), which is a steel cylinder surrounding the filament system and is water-cooled, the outer surface in contact with the water being copper-plated. The anode screws into the tee-piece (34) which carries the side tube (4) leading through the glass tube (1) to the diffusion pump. The joint between (1) and (4) is covered with rubber bicycle tubing, and electrical stress is removed from the glass by the sleeve (3). A similar sleeve (10) removes stress from the glass-to-metal seal (9). The wedges and the ends of the tungsten filaments are covered with the sleeve (8) and the cap (32) to prevent disruptive discharge from the sharp corners.

The piece (5), which has a rounded end, screws into the lower end of the tee-piece (34) and into the aluminium casting (36), which fits the top end of the paxolin column; the purpose of this is to take any accidental cathode-ray discharge from the lower end of the cathode.

All the screwed joints are made vacuum-tight with Apiezon sealing compound Q and Apiezon oil J; these are readily undone for inspection and for putting in new filaments when required. Electrical connections are made with heavy copper braid on to the clamps (23) and (16).

The filaments run at a temperature of about 2 500° K. and require a total current of about 50 amp.

No direct measurements have been made of the voltage drop across the valves, but the power wasted in each has been measured by observing the rate of flow of the cooling water and its rise in temperature between entry and egress. With the rectifier delivering 1 300 mA at 21 kV the power wasted in one valve was 465 watts; so that in the six valves the total power wasted when running at 30 kW input is 2·8 kW, i.e. nearly 10 %.

CONTROL

The high-voltage supply is controlled by an induction regulator which varies the voltage applied to the primaries of the transformers from 200 up to 600 volts; the regulator, which is in a separate room, is operated by a d.c. motor controlled by a push button and relay.

Current is switched on to the transformers by a push-button-operated contactor; auxiliary contacts are arranged to run the regulator down to minimum when the contactor comes out, and a contact on the regulator ensures that the contactor cannot be put in again until the minimum is reached. A magnetically-operated overload device breaks the retaining circuit of the contactor if the current becomes excessive owing to a gas discharge. This device had to be rebuilt so that it should operate without delay.

The current through the tube is controlled by varying the filament current; this is done by means of a resistance in the primary circuit of the transformer which feeds it.

An ammeter in each phase of the supply indicates that the load is balanced, and the power is indicated by a wattmeter in one phase only. A milliammeter on an insulating support, (4) in Fig. (1), is connected in the high-voltage lead to the machine, and a second milliammeter connected in series with a high-resistance to earth indicates the kilovolts applied to the machine.

ACKNOWLEDGMENTS

The authors have pleasure in recording their indebtedness to the following: Messrs. Hadfields, of Sheffield, for their help and advice in connection with the design of the heavy parts of the machine and for their generous gift of the case and rotor; the staff of the research laboratories of the General Electric Company, for advice on the circuit adopted for the rectifier and for their collaboration in the construction of the valves; the electrical and workshop staff of the Royal Institution, for a great deal of work on the wiring of the plant and the construction of all the smaller parts; and the director and managers of the Royal Institution, for the generous allotment of space and equipment which have made the erection of the plant possible.

MEASUREMENTS AND CALCULATION ON RESTRIKING-VOLTAGE TRANSIENTS AT A SUBSTATION FED BY SINGLE-CORE CABLES*

By L. GOSLAND, B.Sc., Associate Member.

(*Paper first received* 17*th September, and in final form* 15*th October*, 1938.)

SUMMARY

For a circuit-breaker operating at the end of a long feeder the feature determining the rate of rise of restriking voltage is the effective surge impedance of the feeder. A previous paper† dealt with the effective surge impedances and calculation of fronts of transients of restriking voltage for substations fed through 3-core belted-type cables. The present paper deals with the surge impedance in various phase combinations of feeders consisting of three single-core paper-insulated double lead-sheathed cables laid in trefoil, and gives methods by which effective surge impedances may be calculated for systems of known constants. Effective surge impedances deduced from measurements taken with the restriking-voltage indicator are compared with values deduced from calculations taking account of transient currents in the cable sheaths, and it is concluded that the agreement obtained is sufficiently good to show that all important relevant features are properly accounted for. As a rough guide it may be said that the effective surge impedance per phase of a system such as is described, is about $0 \cdot 75 \sqrt{(L/C)}$, where L is the effective power-frequency star inductance per unit length and C the core-to-sheath capacitance per unit length of the cable. This L and C are of course the values normally supplied by manufacturers. The inherent rate of rise of voltage for a fault current of I r.m.s. amperes in a breaker fed by such a cable is $2\sqrt{(2)} f \pi I \times$ (effective surge impedance obtained as described), i.e. for a 50-cycle system it is $(0 \cdot 44 \times 10^{-3} I \times$ surge impedance) volts per microsecond.

The constant $0 \cdot 75$ in the above is an average obtained from empirical values for different cable arrangements, but if a more accurate determination is required for any practical cable arrangement it is shown how this can be determined from first principles.

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  (*d*) Front of transient on a system at the first phase to clear of a phase-to-phase-to-earth fault.
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(8) Conclusions.
(9) Acknowledgments.
(10) References.
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Appendix II. The Voltage in an Infinite Distributed System to the End of which Currents $i = I1$ or $i = At$ are Applied.
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† See Reference (1).

(1) INTRODUCTION

The front of the inherent transient of restriking voltage to which a switch at the end of a long feeder opening on a fault is subjected is given by $e = 2\pi f\sqrt{2}IZ \times t$, if the losses in the feeder can be neglected. In this equation I is the r.m.s. fault current opened by the switch, Z the surge impedance of the system of cables in the connection relevant to the switching operation being performed, and t the time in seconds. This linear rise persists for a time $2l/v$, where l is the length of the feeder and v is the velocity of wave propagation along it: after this time the transient is modified by voltage phenomena reflected from the far end of the cable. If the losses in the feeder cannot be neglected, Z is no longer truly a constant, but is itself a function of time and of the system constants. It is thus important, in calculating the rates of rise of voltage to which circuit-breakers on busbars fed by long cables are subject, to know what are the *effective* surge impedances of these feeders in various phase combinations.

It has been shown in a previous paper* that in a 3-core belted-type cable the effect of the losses in the system can be taken account of by assuming the effective Z to be approximately 10 % greater than the value calculated from the cable star inductance and capacitance measured at 50 cycles per sec.

The conditions in a system comprising three single-core cables laid in trefoil, or in an S.L.-type 3-core cable, are slightly different and the present paper gives an account of some measurements made with a restriking-voltage indicator (r.v.i.) on an otherwise dead 3-phase feeder of paper-insulated double lead-sheathed (p.i.d.l.s.) single-core cables, to study the effective surge impedance of such a system so far as transients of restriking voltage are concerned. The subject is analysed in some detail, as a main object of the paper is to explain the reasons for the difference between the observed effective surge-impedances and those calculated on the simplest basis from the star impedance constants of the system, and thus to throw light on the various factors involved. The paper also gives approximate methods by means of which the effective surge-impedance can be calculated for a system of known constants. Whilst the paper is based on measurements on one size of cable only (66 kV, 0·35 sq. in.) the conclusions reached can for the present be taken as applying to other sizes of cable of the same description.

In an S.L.-type cable, the three single-core lead-sheathed conductors are laid up together with jute wormings, wrapped with tape, and armoured overall. Although the lead sheaths are often diagrammatically shown as being in contact, it is usual for them in practice to be separated by thin wrappings of jute tape or similar material and bonded together only at jointing points, as in the single-core-type cables considered in this paper. Thus the only fundamental difference between an S.L.-type cable and the three single-core cables here considered, lies in the presence of the armouring in the former case. The reasoning here presented should thus be directly applicable to S.L.-type cables, although it is to be expected that the numerical relations between effective surge impedances and impedances based on rated reactance and capacitance values for the S.L.-type cable will be somewhat different from those relating to three single-core cables, by reason of the closer spacing between the sheaths, and the presence of the armouring, in the former case. It is expected that it will be found possible to make some measurements on an S.L.-type cable, and the results obtained will be published in due course.

The tests were carried out on a 66-kV cable system 16⅓ miles long, on the system of the County of London Electric Supply Co. These tests were made at the same time as a similar series of tests with the r.v.i. on restriking-voltage transients experienced by switchgear on the busbars on the secondary side of a step-down transformer fed by a cable system such as is here dealt with. A report on the tests involving the transformers, and the transformers and cables jointly, will follow this.

It should be mentioned that these measurements with the restriking-voltage indicator involve merely minute currents and voltages in the system under test, whilst the restriking-voltage transients in practice occur under conditions associated with high voltages and heavy current flow. Since, however, all the impedance parameters playing a part in the phenomena here investigated are, so far as the author is aware, true constants, independent of the current they are carrying, there is no reason to suppose that the effective surge impedances or transients of restriking voltage are likely to be different from those deduced from the r.v.i. records or calculated as described below.

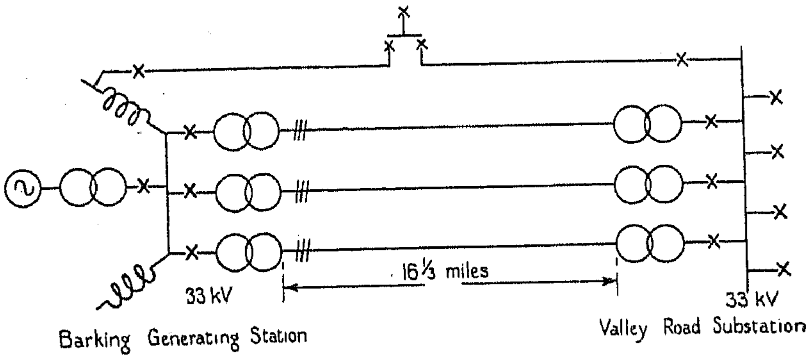

Fig. 1.—Location of cables on which tests were made.

Tests were made on one 3-phase feeder of the three 3-phase 66-kV feeder groups shown; and the paper deals with phenomena affected by the interrelation of the three cables of any one of the three feeders shown above. Measurements were made at the Valley Road end, the conductors being short-circuited to earth at the Barking end.

(2) TEST DATA

(a) The System on which the Tests were Made

The tests were made on a 3-phase cable line, consisting of 28 724 yards of oil-filled* p.i.d.l.s. 66-kV single-core cable, one core per phase. Of this length, 3 452 yards was of 0·5-sq. in. section, the remainder being of 0·35-sq. in. section. The heavier cable was distributed throughout the run in short lengths in situations where heating conditions were onerous, and no account is taken in the present report of the effects of these short lengths, which are considered to be negligible. The location of the cables in the Supply Co.'s system is shown in Fig. 1.

The cables were laid direct in the ground in trefoil formation, with the jute coverings touching. The outer sheaths were bonded together and to the earth at each section. Definite information regarding the connection between the inner and the outer sheaths is lacking, but they are certainly bonded together once per section, and a usual practice is to ensure more or less continuous contact between the inner and outer sheaths; in the present paper they are treated as though they were continuously in contact.

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* See Reference (1).

* The oil filling in this type of cable is contained in a duct through the centre of the stranded conductors (see Fig. 13). This type of cable should not be confused with the "oil insulated" type.

In the present tests the cable conductors at the remote end were connected together and to earth. Access to the near end of the cable was obtained through a 3-phase run, 96 yards long, each phase consisting of two 0·35-sq. in. p.i.l.s. single-conductor cables in parallel, arranged in two 3-phase sets each laid in trefoil. The effect of this small initial discontinuity on the system under investigation is negligible. Table 1 shows the constants of the system so far as they are available.

Table 1

Cable System Constants per Mile

	66 kV	66 kV	33 kV
Cable, sq. in.	0·5	0·35	0·5
Star reactance per phase,* ohm	0·175	0·181	0·180†
Capacitance per phase (core-to-sheath),* μF ..	0·720	0·650	0·475†
Conductor resistance per core,* ohm	0·0865	0·1207	0·0865
Inductance per phase (core-to-sheath),‡ henry	—	0·000125	—
Inductance from sheath-to-sheath (per pair),‡ henry	—	0·000834	—
Sheath resistance per phase,‡§ ohm	—	0·426	—

* Figures in each column are makers' guaranteed figures.
† Quantity per run (there are two 33-kV 3-phase lines in parallel).
‡ Calculated from dimensions of cable.
§ Conductivity of brass-tape intersheath disregarded.

(b) Method of Test with Restriking-voltage Indicator

The theory and method of operation of the restriking-voltage indicator have been fully described by its inventors,* and some account has been given* of experiments showing the excellent agreement between the transients of restriking voltage indicated by the r.v.i. and those obtained on the same systems from cathode-ray oscillograms taken at the interruption of faults at working voltage.

Whilst the instrument was developed primarily for the purpose of examination of transients of restriking voltage in systems, it is very useful (as in the present instance) for examination of those parameters of portions of systems which affect the transient of restriking voltage. The method of calibration suggested in the original paper is, however, not very convenient for this type of work; and for the tests here reported the instrument was calibrated directly in volts per kilo-ampere fault current, as described in Appendix I.

For the present tests, the instrument was placed in the 33-kV switch-house at the substation in which the tests were made, and connection was made by short lengths of vulcanized-rubber cable to plugs placed in the cable spouts of the metalclad busbar assembly, the feeder circuit-breaker being racked out. From these cable spouts connection was made, via the 96-yard run of 33-kV cable described in Section (2)(*a*), to a cable end box, where further short bare copper conductors were used to loop across the transformer to the 66-kV cable end boxes, the normal connections to the intervening transformers being removed.

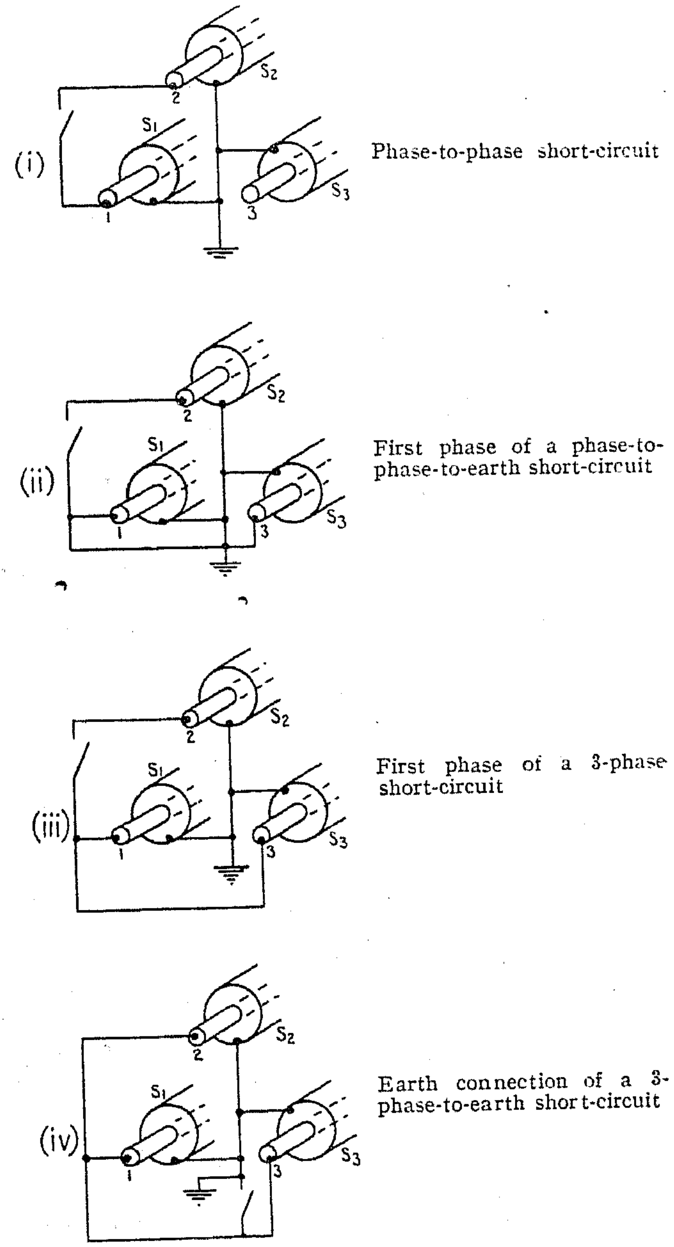
(i)
S_1
S_2
S_3
1
2
3
Phase-to-phase short-circuit
(ii)
S_1
S_2
S_3
1
2
3
First phase of a phase-to-phase-to-earth short-circuit
(iii)
S_1
S_2
S_3
1
2
3
First phase of a 3-phase short-circuit
(iv)
S_1
S_2
S_3
1
2
3
Earth connection of a 3-phase-to-earth short-circuit

Fig. 2.—Location of cable on which tests were made. Diagrams show effective connections of the three cables in any one of the three feeder groups of Fig. 1, at the interruption of various types of fault.

(c) Tests Made and Records Obtained

Tests were made to represent the conditions encountered by a switch opening the following short-circuits at the busbar concerned: (i) Phase-to-phase.

* See Reference (2).

(ii) First phase to clear of phase-to-phase-to-earth short-circuit. (iii) First phase to clear of 3-phase short-circuit. (iv) Switch clearing earth connection in 3-phase-to-earth short-circuit.

The last is not, of course, a practical case. The test was carried out mainly because it provided the simplest means of checking whether the conductivity of the earth in which the cable was laid, and of the sheaths of other cable-runs in parallel with that under investigation, had any effect in determining the transient of restriking voltage.

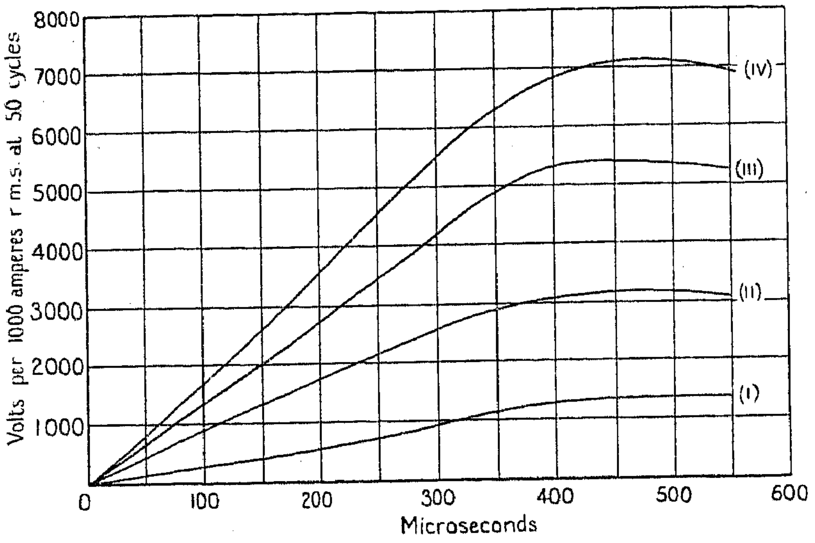

Fig. 3.—Observed inherent transients of restriking voltage per 1 000 amperes r.m.s. fault current interrupted on a 3-phase system of 66-kV single-core oil-filled p.i.d.l.s. cables 16½ miles long (for circuit layout, see Fig. 1). The currents used were of the order of a fraction of an ampere.

(i) Three-phases-to-earth.
(ii) Phase-to-phase-to-earth.
(iii) Phase-to-phase-to-phase.
(iv) Phase-to-phase.

The shortness of the time available for making tests prevented other connections being investigated (e.g. first phase to clear of 3-phase-to-earth short-circuit, etc.). It is thought, however, that those dealt with are of greater interest. Fig. 2 shows in diagrammatic form the relevant connections for the tests (i) to (iv) listed above.

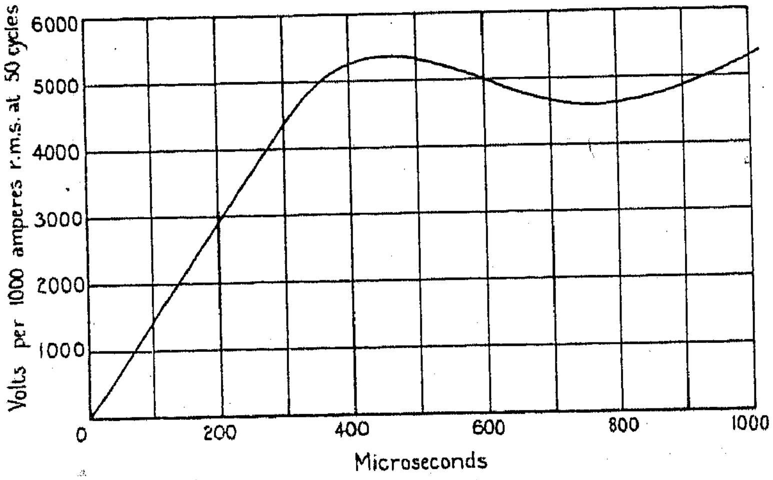

Fig. 4.—Observed transient of restriking voltage in phase-to-phase-to-phase case [Curve (iii) of Fig. 3], extended to 1 000 microseconds.

The records obtained, calibrated in terms of volts per 1 000 amperes and plotted to a uniform time scale, are shown in Fig. 3; and Fig. 4 shows the record obtained in the phase-to-phase-to-phase (i.e. first phase to clear of 3-phase short-circuit) case, plotted out over 1 000 microseconds. It will be seen that in each case the transient consists of a substantially linear rise, tailing off into a heavily damped oscillation. It should, of course, be clearly understood that, although the records obtained are calibrated in volts per kilo-ampere, no such current was flowing in the system when the measurements were made. The actual currents involved were only of the order of fractions of an ampere.

(3) ESTIMATION OF SURGE IMPEDANCES FROM RECORDS, AND COMPARISON WITH VALUES CALCULATED FROM POWER-FREQUENCY REACTANCE AND CAPACITANCE VALUES

By drawing tangents from the origin to the transients shown in Fig. 3 we get the average slope of each curve over the main part of the rise. If we take the effective surge-impedance over the period as Z_e, then this slope is $2\pi f\sqrt{2}IZ_e$, where I is the r.m.s. 50-cycle current dealt with (i.e. $10\sqrt[3]{2} \times 314Z_e$, since the curves are calibrated in terms of volts per kilo-ampere at 50 cycles per sec.) and we can deduce Z_e for the various connections from the slope of the observed transients. The values of Z_e as obtained for the connections examined are given in Table 2 together with the value of the nominal surge impedance $\sqrt{(L/C)}$ calculated, (*a*) taking the inductance per phase as that (L_{st}) equivalent to the star reactance at power frequency, and (*b*) taking the inductance per phase as the core-to-sheath inductance (L_{cs}) of each cable only.

Similarly, by noting the points at which the transients of Fig. 3 appear to depart from the law followed during the initial rise, it is possible to find roughly the time of propagation along the 16½ miles of cable and back, and hence the propagation velocity within the system. These

Table 2

EFFECTIVE VALUES OF SURGE IMPEDANCE (Z_e) DEDUCED FROM RECORDS OBTAINED, COMPARED WITH VALUES OF $\sqrt{(L/C)}$ OBTAINED FROM THE POWER-FREQUENCY CONSTANTS OF THE SYSTEM, NEGLECTING LOSSES; (*a*) TAKING THE INDUCTANCE PER PHASE AS THE STAR REACTANCE, (*b*) TAKING THE INDUCTANCE PER PHASE AS THE CORE-TO-SHEATH INDUCTANCE ONLY

1	2	3	4	5
		Values of $\sqrt{(L/C)}$		
Connection	Z_e from records	(*a*) Z_n, taking L per phase $=(1/\omega)\times$ star reactance per phase	(*b*) Taking L per phase = core-to-sheath inductance per phase	Mean of (*a*) and (*b*)
Phase-to-phase ..	41·4	59·4	27·75	43·6
Phase-to-phase-to-earth	19·7	29·7*	13·87*	21·8
3-phase	31·7	44·6	20·8	32·7
3-phase-to-earth ..	7·7	9·93	4·62	7·3

* On the assumption that there are no losses, there can be no current in the cores of the earthed cable in the phase-to-phase earth connection, and so the surge impedance is simply the phase-to-earth surge impedance of one cable.

figures are given in Table 3, together with propagation velocities and times calculated, as for the surge impedances in Table 2, on the assumption that the inductance per phase was (*a*) the star inductance per phase (L_{st}) and (*b*) the core-sheath inductance per phase (L_{cs}).

It will be seen from Table 2, cols. 2 and 5, that in each case the effective surge-impedance lies approximately midway between the values calculated on the assumptions (*a*) and (*b*) made above regarding the effective inductances per phase; whilst, from Table 3, the propagation velocity as deduced from the apparent time of departure of the transient from its initial law is approximately equal to that calculated on the basis that the effective inductance per phase is the core-sheath inductance only. It will be shown that, if the losses are suitably taken account of, the effective surge-impedances derived from the calculated transients agree quite closely with the values deduced from the records. Whilst the effective propagation velocities appearing can be accounted for (agreeing roughly, as they do, with values calculated on the core-to-sheath inductances), it cannot be said that it is yet possible to take proper account of the return wave and calculate the whole restriking-voltage transient. Further reference to this point is made later in the paper.

Table 3

EFFECTIVE VALUES OF WAVE VELOCITIES AND PROPAGATION TIMES TO TRAVERSE CABLE FROM END TO END AND BACK, DEDUCED FROM RECORDS OBTAINED, COMPARED WITH VALUES CALCULATED FROM POWER-FREQUENCY CONSTANTS OF THE SYSTEM, NEGLECTING LOSSES, AND (*a*) TAKING THE INDUCTANCE PER PHASE AS THE STAR REACTANCE, AND (*b*) TAKING THE INDUCTANCE PER PHASE AS THE CORE-TO-SHEATH INDUCTANCE ONLY

Connection	From records		Calculated, neglecting losses			
			(*a*)		(*b*)	
			From $L = L_{star}$ per phase		From $L = L_{core\text{-}sheath}$ per phase	
	Propagation time (sec.)	Wave velocity (miles per sec.)	Propagation time (sec.)	Wave velocity (miles per sec.)	Propagation time (sec.)	Wave velocity (miles per sec.)
Phase-to-phase	275–300	$10 \cdot 8$ to $11 \cdot 8 \times 10^4$	620	$5 \cdot 26 \times 10^4$	294	$11 \cdot 1 \times 10^4$
Phase-to-phase-to-earth ..	Impossible to assess		620	$5 \cdot 26 \times 10^4$	294	$11 \cdot 1 \times 10^4$
3-phase	275–300	$10 \cdot 8$ to $11 \cdot 8 \times 10^4$	620	$5 \cdot 26 \times 10^4$	294	$11 \cdot 1 \times 10^4$
3-phase-to-earth	275–300	$10 \cdot 8$ to $11 \cdot 8 \times 10^4$	620	$5 \cdot 26 \times 10^4$	294	$11 \cdot 1 \times 10^4$

(4) CALCULATION OF FRONT OF RESTRIKING-VOLTAGE TRANSIENTS ARISING ON THE CABLE SYSTEM, INCLUDING THE EFFECTS OF LOSSES IN THE CONDUCTORS AND SHEATHS

(a) Front of Transient on a Simple Distributed System (Core and Single Sheath)

The calculation of the front of the transient of restriking voltage arising on a simple distributed circuit, including the effect of losses but neglecting skin effects on the effective inductances of the system, offers little difficulty and can be made as shown in Appendix II. The only case in which this is directly applicable, however, is that of a switch opening the earth connection of a 3-phase-to-earth short-circuit, since this is the only case in which transient circulating currents are not set up in the sheath circuits, as will appear below: and this case is of little practical importance.

Whilst the return wave can be calculated for this simple case, the result of neglecting skin effects and similar phenomena affecting the distribution of current over the conductors is here quite important [see Section (6)]; and transients calculated on this basis do not agree with the observed transients after the effect of the return wave has become appreciable.

The modification to the analysis for the front of the transient necessary to take approximate account of the fact that the cables are not simple distributed circuits, can be fairly easily carried out for each individual case; but it will be necessary to do a good deal more work before the effects of the return wave, which determines the peak value reached by the restriking-voltage transient, can be properly taken into account.

(b) Front of Transient on a System at the Clearing of a Phase-to-phase Fault

The transient of restriking voltage which occurs at the interruption of a phase-to-phase short-circuit is the voltage arising on the application of a current $i = At$ to the system of Fig. 2(i). It is clear that since the cables are laid in trefoil neither core nor sheath of the third (idle) cable can have any voltage induced in it by current flowing in the cores or sheath of the faulted cables, so that no account need be taken of its presence. It is also clear, however, that when current flows in the circuit through Conductors 1 and 2, lines of magnetic flux must exist within the circuit S_1S_2, and the transient current induced in the sheath-to-sheath circuit by this flux has an important effect on the effective surge impedance of the system.

It is shown in Appendix III that immediately on the application of the current $i = At$ to the system 1, 2, equal and opposite currents are induced in the sheath-to-sheath circuit, so that initially there is no flux outside the sheaths, and the effective inductance per phase is the inductance between core and sheath only, the effective resistance per phase being the resistance of the core plus the resistance of the sheath per phase. The ratio between the conductor currents and the sheath currents falls (see Fig. 5) fairly rapidly from its initial value of unity, the effective inductance per phase meanwhile increasing whilst the effective resistance decreases. By using a step-by-step method it is possible to calculate the voltage between the terminals 1, 2 [Fig. 2(i)] at the sudden application between them of a current $i = At$, as is described in Appendix III; the reasonable agreement (up to the time of arrival of the first return wave) between calculation and experiment is shown in Fig. 6. The effective surge impedance, as deduced from the front of the calculated transient over the first 300 microseconds, is 43·1 ohms, compared with the experimental value of 41·4 ohms.

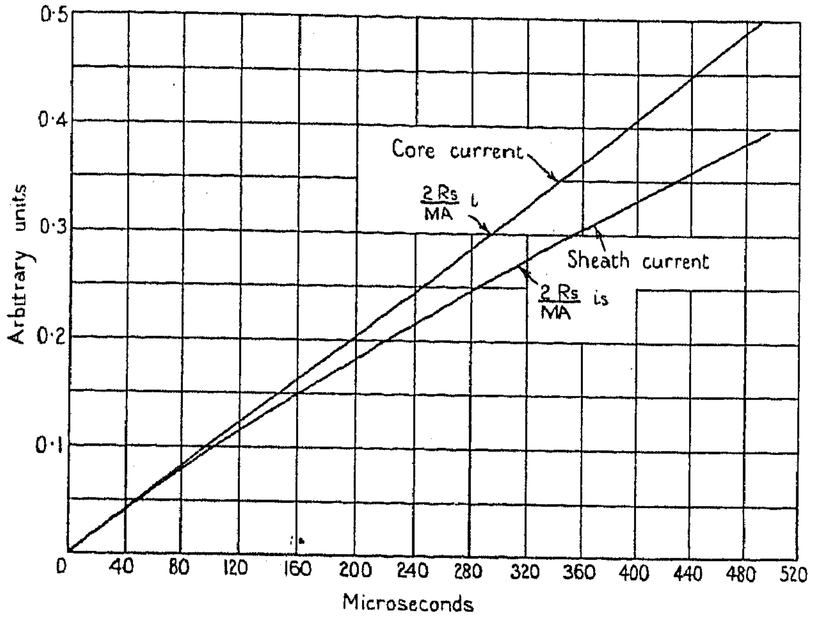

Fig. 5.—Calculated relation between core and sheath currents under transient conditions for cables as in Fig. 3 (phase-to-phase short-circuit, see Appendix III).

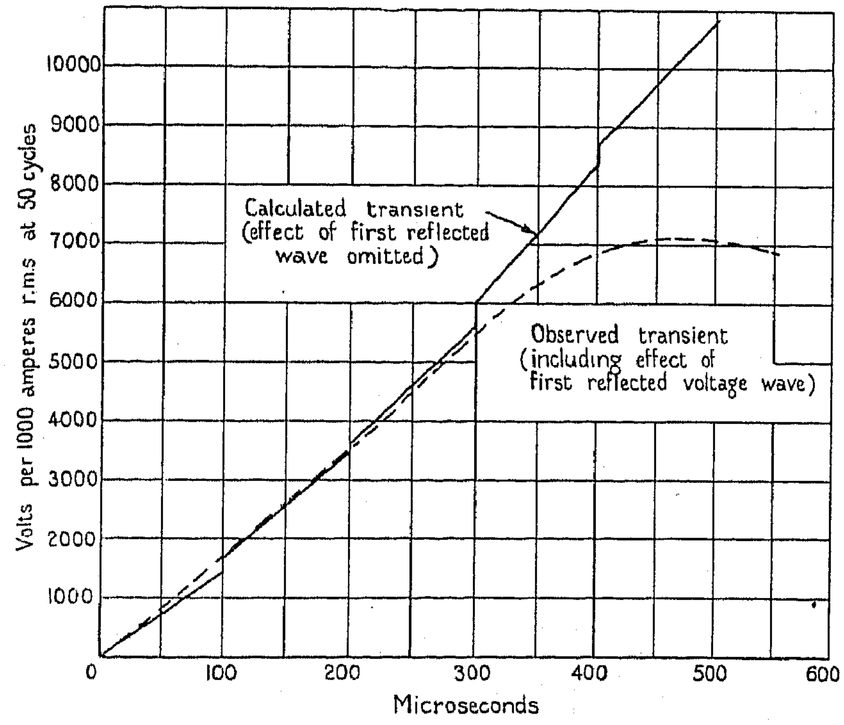

Fig. 6.—Front of transient of restriking voltage as calculated in Appendix III, compared with observed transient (phase-to-phase case, circuit as for Fig. 3).

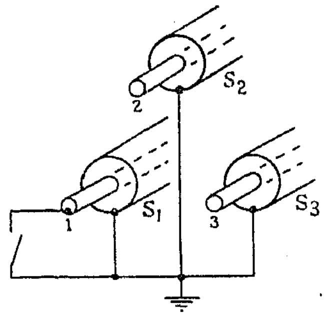

Fig. 7.—System determining effective surge impedance at interruption of phase-to-earth short circuit.

(c) Front of Transient on a System at the Clearing of a Phase-to-earth Fault

Although no test was carried out on this connection, the front of the restriking-voltage transient per 1 000 amperes and the effective surge-impedance have been calculated for this case, both to complete the work and because the calculation is of interest in connection with a case subsequently dealt with.

The system to which the current $i = At$ must be considered applied in calculating the transient, is that shown in Fig. 7, and the transient, including the effect of the currents in the sheaths S_2 and S_3, as well as in the sheath of the faulted cable, may be calculated in the manner set out in Appendix IV. The result of this calculation is shown in Fig. 8, curve (i).

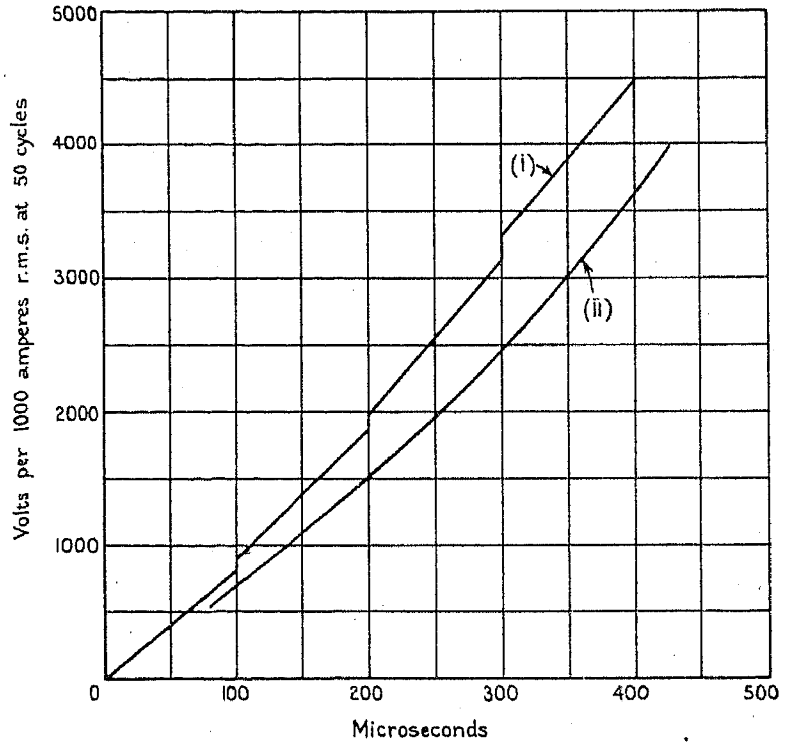

Fig. 8.—Calculated front of restriking-voltage transient on interruption of phase-to-earth short-circuit (circuit as for Fig. 3).

(i) Calculated, including the effect of currents in sheaths of unfaulted cables.
(ii) Calculated, assuming all current flows in sheath of faulted cable only (3 × 3-phase-to-earth values).

The voltage transient, neglecting the effect of the sheaths of the two unfaulted cables, can easily be calculated using the formulae developed in Appendix II: the result of such a calculation for the present cables is shown in Fig. 8, curve (ii).

It is rather surprising that the apparent effect of the paths through the additional sheaths is to increase the initial effective surge-impedance, although this may be explained to some extent on the grounds that the additional paths increase the effective inductance of the system, which is the major feature determining the effective surge-impedance over the time in which we are interested. The point is one on which it would be well to obtain experimental evidence, although it would probably be very difficult to arrange the necessary tests, lengths of several miles of isolated single-core cable not being very common.

(d) Front of Transient on a System at the First Phase to Clear of a Phase-to-phase-to-earth Fault

The system to which the current $i = At$ must be considered applied in this case is shown in Fig. 2(ii).

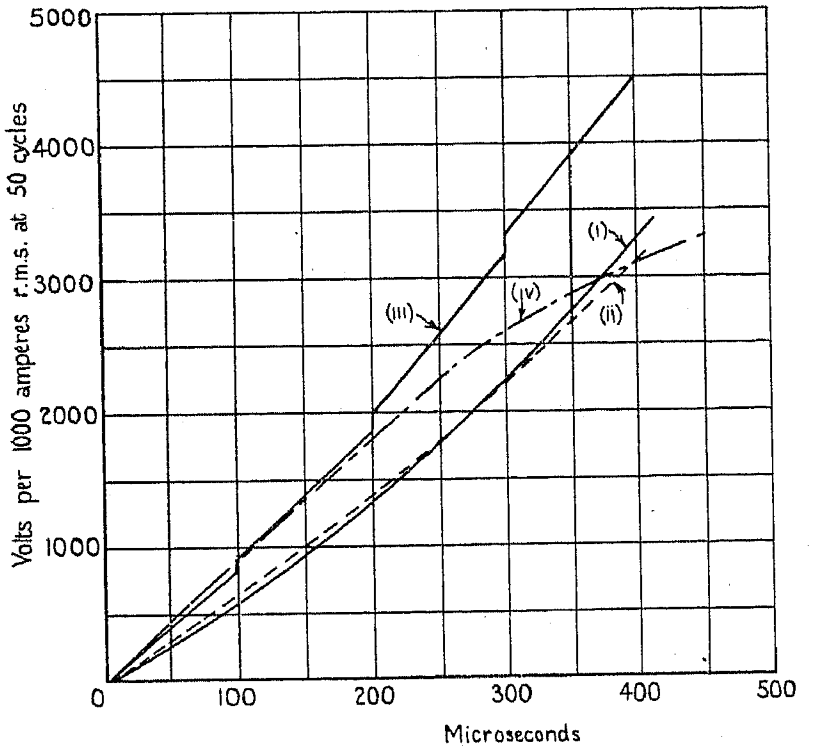

Fig. 9.—Front of transient of restriking voltage at first phase to clear of phase-to-phase-to-earth fault (circuit as for Fig. 3).

(i) Calculated as in Appendix V, considering sheath and external concentric sheath.
(ii) Calculated as in Appendix II, considering core and single sheath only.
(iii) Calculated as for phase-to-phase fault (Appendix IV).
(iv) Observed transient.

The sheaths are now not electrically symmetrical with respect to the cores, and an analysis similar to that of Appendix III (for the phase-to-phase case) cannot be applied.

The differential equations governing phenomena with this connection have so far proved insoluble, but we can determine in the following way approximately what the effective surge impedance and front of the restriking-voltage transient should be.

We have calculated the front of the transient for the phase-to-earth case, which is the same as for the case here dealt with except that in the latter an additional core is connected to the sheath system. If we now calculate separately the effect of an additional conductor connected to the sheath system, we can estimate by how much the slope of the transient calculated, neglecting the core, should be raised or lowered to account for the effect of the core.

Such a calculation can be made on the lines described in Appendix V, and it is there shown that the connection of the core has a negligible effect [see curves (i) and (ii), Fig. 9]. Thus the front of the transient of restriking voltage per kilo-ampere of fault current, and the effective surge-impedance, should be approximately the same at the interruption of the first phase to clear of a phase-to-phase-to-earth short-circuit as at the clearance of a phase-to-earth short-circuit.

The observed transient in this connection is plotted in Fig. 9, curve (iv), along with the transient, calculated neglecting the effect of the core connection [curve (iii)]. It will be seen that the agreement over the first 200 microseconds is reasonably good, but that after this the two curves diverge more and more rapidly with time, probably since the calculation does not take account of the first return wave, the effects of which are apparent in the observed transient.

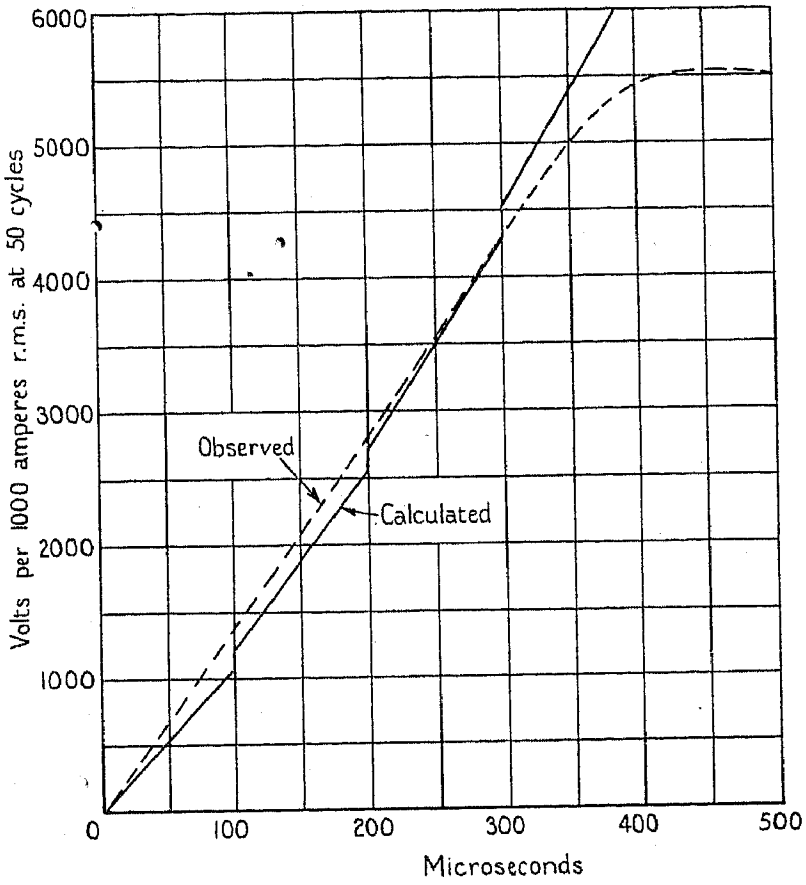

Fig. 10.—Calculated and observed front of transient of restriking voltage at opening of first phase to clear of 3-phase short-circuit (circuit as for Fig. 3).

(e) Front of Transient on a System at the First Phase to Clear of a 3-Phase Fault

It is easy to see, although difficult to prove in a simple manner, that including the effects of sheath currents the effective surge-impedance in this case should be exactly 75 % of the effective surge impedance in the phase-to-phase case. In Fig. 10 the observed transient per kilo-ampere in the relevant connection is plotted with the transient calculated on the above basis. It will be seen that the agreement is quite good up to 300 microseconds, which is about the time of arrival of the first return wave.

(f) Front of Transient on a System at the Opening of the Earth Connection in a 3-phase-to-earth Short-circuit

This is not a condition which will arise in practice; the test was, however, made because it afforded the simplest means of judging whether or not it was necessary to take account of the conductivity of the earth in which the cables are laid, or of the sheaths of parallel cable runs, in calculating effective surge-impedances.

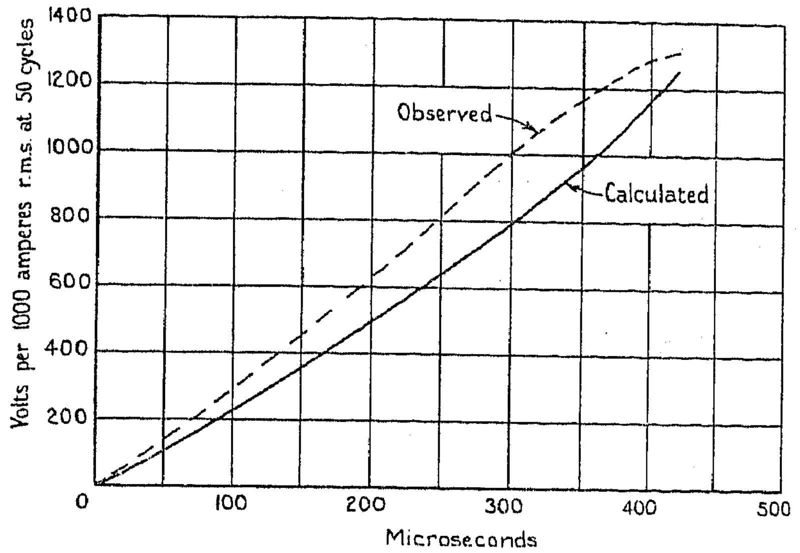

Fig. 11.—Calculated and observed transients of restriking voltage at the opening of the earth connection on 3-phase-to-earth short-circuit (circuit as for Fig. 3).

It is quite clear that no transient circulating currents can arise between the sheaths of the cables under observation, and therefore, neglecting the possible effects of conductivity of the earth and of parallel cable runs, the front of the transient of restriking voltage per kilo-ampere can easily be calculated by a simple application of the formulae of Appendix II,* bearing in mind that there are three cables in parallel. The transient so calculated is shown in Fig. 11, together with the observed transient. It will be observed that the agreement is reasonable, the calculated transient being between about 75 % and 80 % of the observed. Some difference is of course to be expected since the effects of earth transients are neglected in making the calculation and, as has been explained above, their effect would probably be to increase the effective inductance, and hence the surge impedance and rates of rise of voltage, of the system. The fact that the difference between observed and calculated transients is not greater than 25 % in the present instance, where earth transients are likely to be of maximum importance, shows that they cannot be of major importance in the other connections dealt with in the present paper, since the earth-return paths are there in parallel with other stray return paths (e.g. sheaths) of which suitable account is taken, whilst in the present instance they represent the only stray returns.

(5) COMPARISON BETWEEN EFFECTIVE SURGE IMPEDANCE OBSERVED, AND THAT CALCULATED ON VARIOUS ASSUMPTIONS

From the various transients of restriking voltage calculated as described in Section (4), it is possible to obtain " effective " surge-impedance values over any given time up to the arrival of the first return wave. The values so obtained over 300 microseconds in each case appear in Table 4, col. 3, together with the values obtained from the observed transients (col. 2) and the values based on the power-frequency inductances and capacitances, neglecting losses (cols. 5 and 6). It will be seen that the agreement between the experimental values and those calculated including the effects of losses is in general sufficiently good to provide justification for assuming that most of the phenomena which play an important part in determining the effective surge-impedance have been taken into account in the calculation. Reasons for the difference between the effective surge-impedance obtained empirically, and the surge impedances calculated from the power-frequency inductance and capacitance constants, are on these grounds easily supplied.

Table 4

COMPARISON OF EFFECTIVE SURGE-IMPEDANCE VALUES OVER RANGE 0–300 MICROSECONDS

1	2	3	4	5	6
Connection	By experiment	Calculated,* including effect of losses	Calculated from power-frequency constants (neglecting losses)		Col. 2 as % of Col. 4
			Using $L = L_{star}$	Using $L = L_{core\text{-}sheath}$	
Phase-to-phase	41·4	43·1	59·4	27·75	70
Phase-to-phase-to-earth ..	19·7†	17·0	29·7	13·87	66
3-phase	31·7	33·0	44·6	20·8	71
3-phases to earth	7·7	6·0	9·93	4·62	78
Phase to earth	—	24·4	29·79	13·86	—

* Based on cable dimensions, spacing, and materials. † Over 200 microseconds only.

Col. 6 of Table 4 shows the relation between the observed values of surge impedances, and those calculated from the expression $\sqrt{(L/C)}$ using normal star reactance and capacitance values. It will be observed that the former are generally about 75 % of the latter, and it is suggested that for the present the factor 0·75 should be used to calculate effective surge-impedances from the values given by $\sqrt{(L/C)}$. Calculation including the effects of losses could of course be made for individual cases, but the work is exceedingly laborious.

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* See also Reference (3).

The values of effective surge-impedance discussed above are those effective over 300 microseconds (i.e. up to the time of return of the reflected voltage wave on cables about 16 miles long). It is obvious that the factor 0·75 arrived at must to some extent depend on the length of time over which the transient remains linear (i.e. on the length of the cable), and values of the factors for cables of various lengths are given in Table 5.

Table 5

VALUES OF FACTOR RELATING APPROXIMATE EFFECTIVE SURGE-IMPEDANCE OVER WHOLE TIME OF LINEAR RISE OF VOLTAGE, TO SURGE IMPEDANCE CALCULATED FROM $\sqrt{(L_{star}/C_{star})}$, FOR CABLE SYSTEMS OF VARIOUS LENGTHS

Cable length (miles)	5	10	15	20	25
Factor	0·66	0·70	0·75	0·82	0·88

(6) THE FIRST REFLECTED VOLTAGE WAVE AND THE PEAK VALUE OF THE TRANSIENT OF RESTRIKING VOLTAGE

By putting x equal to twice the total length of the cable-run, we can use equation (2) of Appendix II to calculate the first return wave to reach the point where the current function $i = At$ is applied, assuming, of course, that the cable is connected at the far end to a busbar of zero impedance (i.e. a short-circuit). Fig. 12 shows the total transient calculated over 400 microseconds for the system in the phase-to-phase connection, including the effect of the return wave. The step-by-step method used to take account of the sheath circulating-current transients breaks down for calculations beyond the time of return of the current input at 100 microseconds, since the differing circuit parameters assumed for successive time-intervals give successively lower propagation velocities. Thus the parameters used in Appendix II for the system from 0–100 microseconds give a return voltage wave arriving at 320–420 microseconds, the parameters assumed from 100–200 microseconds give a return wave at 490–590 microseconds, and so on; and the calculation of the complete return wave over 200–300 microseconds by such methods (including the necessary smoothing) would be very laborious.

The main point to be deduced from Fig. 12 is that the effects of the return wave in practice became apparent somewhat earlier than the calculations would lead us to expect (about 275–300 microseconds instead of 320 microseconds after the start). This is probably to be accounted for by the influence of skin effects. Thus the ratio between the overall core-to-sheath inductance (assuming current uniformly distributed over conductor sections) and the inductance between the outermost filament of core and the innermost filament of sheath in the present cables is 1·61, and so it must be possible for some effects of the first disturbance at the input end of the cable to travel through the system with a velocity 1·27 times (i.e. $\sqrt{1 \cdot 61}$) greater than the velocity calculated assuming uniform current distribution. This would give the front of the first return wave as arriving at 250 microseconds, against 320 microseconds used in the calculation on which Fig. 12 is based. It is therefore obviously impossible to calculate the restriking-voltage transient completely until this phenomenon has been taken into account, and this problem still awaits solution.

The above argument explains also why, although the effective surge-impedances are about midway between the values calculated from power-frequency constants neglecting losses, using $L = L_{st}$ and $L = L_{cs}$ respectively, the effective propagation times, deduced from the time at which the transient appears first to depart from its initial law, lie much closer to the values obtained using $L = L_{cs}$.

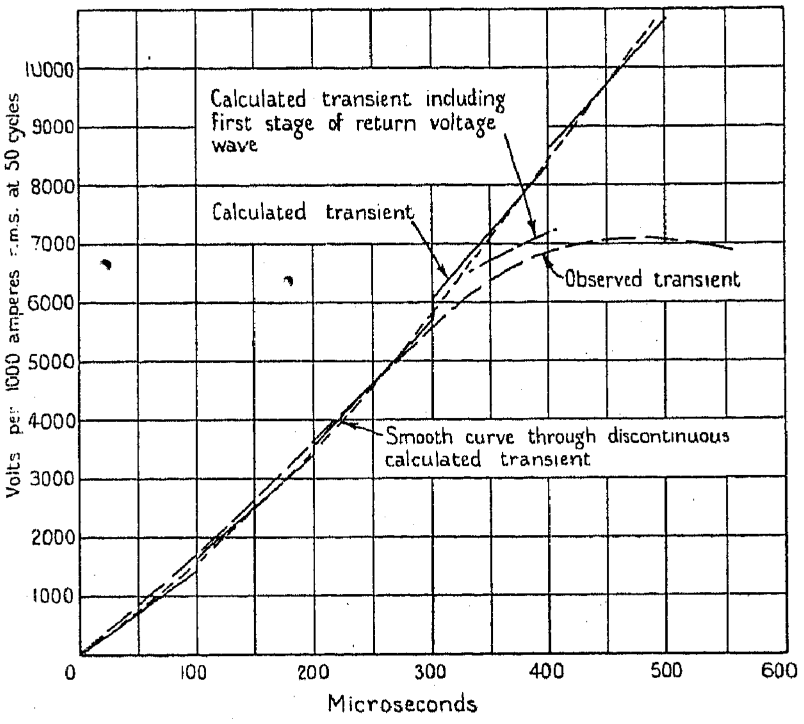

Fig. 12.—Phase-to-phase case: calculated transient, including effect of early portion of return voltage wave, compared with observed transient (circuit as for Fig. 3).

(7) APPLICATION OF THE RESULTS

The results given in the present paper are of direct application to such problems as the following. Suppose we wish to determine the rate of rise of the front of the transient of restriking voltage for a circuit-breaker situated as indicated in Fig. 13. The fault currents at the point in question are first calculated in the normal manner for the particular type of fault. The nominal surge-impedance per phase per feeder group is then calculated from $Z = \sqrt{(L_{st}/C)}$, where L_{st} is the star inductance and C is the star capacitance per mile per phase per feeder group, in henrys and farads respectively. The effective surge-impedance per phase per feeder group is then $Z_e = 0 \cdot 75Z$, and the effective surge-impedance per phase of the supply as a whole is Z_e/n, where n is the number of similar feeder groups in parallel (where the feeder groups are dissimilar, the effective surge-impedance per phase of the supply is obtained from the surge impedances per phase of the respective feeders by the usual formula for resistances in parallel).

The nominal propagation velocity for the system is also calculated from $v = 1/\sqrt{(LC)}$ miles per second, and the effective propagation velocity is taken as $2v \times 10^{-6}$ miles per microsecond. The values of total surge-impedance encountered at the interruptions of various types of faults are then as follows:—

Phase-to-earth fault	Z_e/n
Phase-to-phase fault	$2Z_e/n$
First phase of 3-phase fault	$1\cdot5Z_e/n$
First phase of phase-to-phase-to-earth fault	Z_e/n

and if the fault currents are I_{PE}, I_{PP}, I_{3P}, I_{PPE} respectively, the rates of rise of restriking voltage are:—

$445^* \times I_{PE} \times Z_e/n$,
$445 \times I_{PP} \times 2Z_e/n$,
$445 \times I_{3P} \times 1\cdot5Z_e/n$,
$445 \times I_{PPE} \times Z_e/n$ volts per second respectively.

These rates persist linear for a time of approximately $2l/(2v)$ seconds, where l is the length of each feeder between generating station and substation. After this time the transient is modified by reflected phenomena depending upon conditions at the generating-station busbars; but the tangent to the modified portion from the instant of zero current may in some cases be steeper than the first substantially linear portion of the transient here discussed. The voltage resulting from the arrival of the reflected waves can be calculated in the manner outlined in Reference (1) and Appendix III, and adjustment made to the tangent, if necessary, to obtain the rate of rise of restriking voltage.

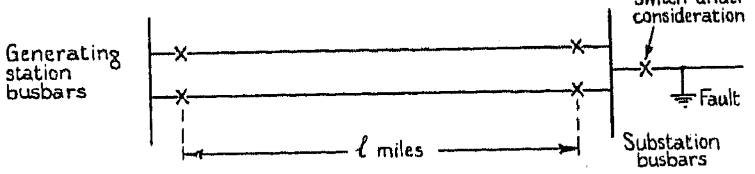

Fig. 13.—Typical circuit-breaker location for which rates of rise of voltage may be calculated on the lines described in the paper.

Two feeders, each of three single-core p.i.d.l.s. cables, laid in trefoil.
Star reactance $314L$ ohms per phase per mile.
Star capacitance C μF per mile.

(8) CONCLUSIONS

(*a*) The effective surge-impedance affecting the rate of rise of transient restriking voltage for circuit-breakers fed by 3-phase feeders of single-core p.i.d.l.s. oil-filled cable, say, 10 to 20 miles in length, laid in earth in trefoil with coverings touching, is roughly 75 % of the surge impedance $\sqrt{(L/C)}$ calculated using the power-frequency star inductance and capacitance of the system in the appropriate phase combination. Col. 6 of Table 4 shows the precise percentages obtained in the tests on which the present paper is based.

(*b*) The reduction of effective surge-impedance below the values calculated on star reactance and capacitance quantities is due to transient currents in the sheath-to-sheath circuits. Fundamental formulae are given in the paper by means of which the effects of these transients may be estimated; but the necessary calculations are very laborious, and it is suggested that the empirical factor 75 % given above should be sufficiently accurate for most purposes within the range 10–20 miles (length). Some idea of the variation of the factor with length of cable is given in Table 5.

(*c*) The maximum observed velocity of wave propagation appears to be about 110 000 miles per sec. (deduced from the time at which the front of the transient of restriking voltage appears first to depart from its initial law). This is in fair agreement (i.e. to within 10 %) with the velocity calculated from the inductance and capacitance between core and sheath of the cable.

(*d*) The effect of the conductivity of the earth in which the cables are laid, and of the sheaths of any other cable systems laid in parallel with, but at a little distance from, the system under investigation appears to be quite small compared with the effect of the conductivity of the sheaths of the cables in the same feeder group, although the conductivity of the earth in which the cables are laid is nearly the highest in the country, being between 1 000 and 3 000 ohm-cm., whereas the values for the whole of the British Isles range from below 1 000 to above 300 000 ohm-cm.

(*e*) The reasoning here presented should be applicable with slight modification to S.L.-type 3 core cable as well as to the single-core unarmoured systems to which it directly refers.

(*f*) Section (7) of the report shows how the data contained in the paper can be applied to the calculation of rates of rise of voltage in various types of fault likely to be met with in practice within the conditions of length and type of cable specified.

(*g*) The peak value to which the transient of restriking voltage rises, is affected by distortions of the wave-front due to non-uniform distribution of the transient currents in the cable core over the conductor section; these effects are briefly discussed in the paper, but have not been completely investigated.

(*h*) Any calculation regarding the peak value reached by the transient of restriking voltage, which is made neglecting the features mentioned in (*g*) above, will in general give a value for the peak voltage which will be higher than that occurring in practice.

(*j*) Much complicated calculation can be saved by the use of the restriking-voltage indicator* in investigations such as the present.

(9) ACKNOWLEDGMENTS

The Electrical Research Association is indebted to the County of London Electric Supply Co., Ltd., and to Mr. W. J. H. Wood, engineer-in-chief, for permission to make the measurements on which this paper is based. The Association is also indebted to members of the staff of the undertaking for their co-operation in making the measurements.

The work described forms part of the investigations

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* $445 = 2\pi \times (f = 50) \times \sqrt{2}$.

* See Reference (2).

into the phenomena of arc rupture which are being carried out on behalf of the Association by Dr. W. B. Whitney, to whom the author is indebted for numerous helpful discussions and criticisms during the course of the work. He wishes also to acknowledge the great assistance given by his colleague, Mr. W. F. M. Dunne, during the preparation of this paper.

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APPENDIX I

The Voltage Calibration of the Restriking-voltage Indicator

The restriking-voltage indicator has been fully described by the engineers responsible for its development.† In the use for which it was primarily developed, voltage calibration of the records obtained with it is achieved by taking the mean final deflection of the record above the zero line as being equivalent to the peak power-frequency recovery voltage of the system. This method of calibration is not very convenient when the instrument is used, as in the present instance, for examination of the impedance of a portion of a system. It is, however, possible to calibrate the instrument directly in terms of voltage in the following manner. Taking the instrument with any given output transformer fitted (e.g. the output transformer covering the range 5–20 ohms) and operating on, say, "full surge," we may record the transients arising when the surge is injected into, say, four different circuits, each consisting of air-cored reactors of reactance 5, 6·5, 8, 10 ohms at 50 cycles per sec., having a series resistance not greater than 10 % of their reactance at 50 cycles per sec., and each shunted by resistances giving nearly critical damping to the transients arising. The records obtained will consist of exponential rises to sustained deflections, the sustained deflections being proportional to the inductances in the circuits. We can plot these deflections against inductance (the relation will be found to be linear if the instrument is properly used) and thus we can say that the instrument gives so many millimetres deflection per millihenry, or per ohm at 50 cycles per sec. We may go further, however, and say that 1 ohm represents 1 414 peak volts at 1 000 amperes (r.m.s.), so that the instrument deflects so many millimetres per kilovolt appearing across a circuit when 1 000 amperes (r.m.s.) is injected, a separate calibration being necessary for each output transformer on half and on full surge.

So calibrated, the records obtained are in a form convenient for comparison with calculated transients in portions of systems such as that with which the present report deals. To obtain the actual transient of restriking voltage, on a system including generating plant, it is necessary only to calculate the appropriate fault current in kilo-amperes (making allowance for decrement if necessary) and multiply the ordinates of the voltage/time curve obtained by using the calibration in volts per kilo-ampere, by the fault current in kilo-amperes.

APPENDIX II

The Voltage in an Infinite Distributed System to the End of which Currents $i = I1$* or $i = At$ are Applied

The voltage in a practical distributed system (for instance, a cable of resistance R, inductance L, capacitance C, and leakage conductance G per unit length) can be worked out by methods similar to those used in Reference (3), Section (*g*). For a current $i = I1$ applied at one end of such a cable, the voltage $(e_x)_t$ at any point distant x units from the starting end is

$$(e_x)_t = \frac{I}{Cv}\left\{\epsilon^{-\rho t}J_0\left[j\sigma\sqrt{\left(t^2 - \frac{x^2}{v^2}\right)}\right]1_{\frac{x}{v}} + \frac{R}{L}\int_0^t \epsilon^{-\rho t}J_0\left[j\sigma\sqrt{\left(t^2 - \frac{x^2}{v^2}\right)}\right]1_{\frac{x}{v}}\,dt\right\} \quad . \quad . \quad (1)$$

where $\rho = \frac{R}{2L} + \frac{G}{2C}$, $\sigma = \frac{R}{2L} - \frac{G}{2C}$, $v = \frac{1}{\sqrt{(LC)}}$

For a current $i = At$ applied at one end of such a cable,

$$(e_x)_t = \frac{A}{Cv}\left\{\int_0^t \epsilon^{-\rho t}J_0\left[j\sigma\sqrt{\left(t^2 - \frac{x^2}{v^2}\right)}\right]1_{\frac{x}{v}}\,dt + \frac{R}{L}\int\!\!\int_0^t \epsilon^{-\rho t}J_0\left[j\sigma\sqrt{\left(t^2 - \frac{x^2}{v^2}\right)}\right]1_{\frac{x}{v}}\,dt\,dt\right\} \quad . \quad (2)$$

With $x = 0$ the above expressions give the voltage $(e_0)_t$ at the starting end for the given applied currents. For the applications in which we are interested, G can usually be regarded as zero, in which case $\rho = \sigma$. The expression for $(e_0)_t$ can then be more simply expressed as a power series in ρ and t.

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* This report is at present available only to members of the E.R.A.

† See Reference (2).

* 1 represents the Heaviside unit function.

For unit-function applied current, given by $i = I1$,

$$(e_0)_t = I\sqrt{\left(\frac{L}{C}\right)}\left(1 + \rho t - \frac{\rho^2 t^2}{4} + \frac{\rho^3 t^3}{12} - \dots\right) \quad . \quad (3)$$

For linear applied current, given by $i = At$,

$$(e_0)_t = A\sqrt{\left(\frac{L}{C}\right)}\left(t + \frac{\rho t^2}{2} - \frac{\rho^2 t^3}{12} + \frac{\rho^3 t^4}{48} - \dots\right) \quad . \quad (4)$$

For the values of t in which we are interested the sum correct to three digits is usually given by the first three or four terms of the above series.

APPENDIX III

An Approximate Method of Calculating the Surge Impedance determining the Restriking-voltage Transient at the Interruption of a Phase-to-phase Current on a 3-phase System Consisting of Three Single-conductor Cables Laid in Trefoil in the Ground

The system in the surge impedance of which we are interested is represented by Fig. 14. A is the main conductor, B the main insulation, C the inner lead sheath, D the thin brass-tape armouring and inter-sheath filling, E the outer lead sheath, and F the hessian covering. We shall consider that a fault current has been flowing in Phases 1 and 2, Phase 3 being the sound phase. The fault current is interrupted by an α-switch* located directly at the cable terminals, which is supposed to add negligible impedance to the system. The inherent transient of restriking voltage is to be arrived at in the normal manner by calculating the voltage arising at the system terminals on the application to the system between these terminals of a current $i = At$ from a source of infinite impedance ($A = 2\pi f\sqrt{2}I$, where I = peak fault-current interrupted, assumed sinusoidal, and f = system supply frequency).

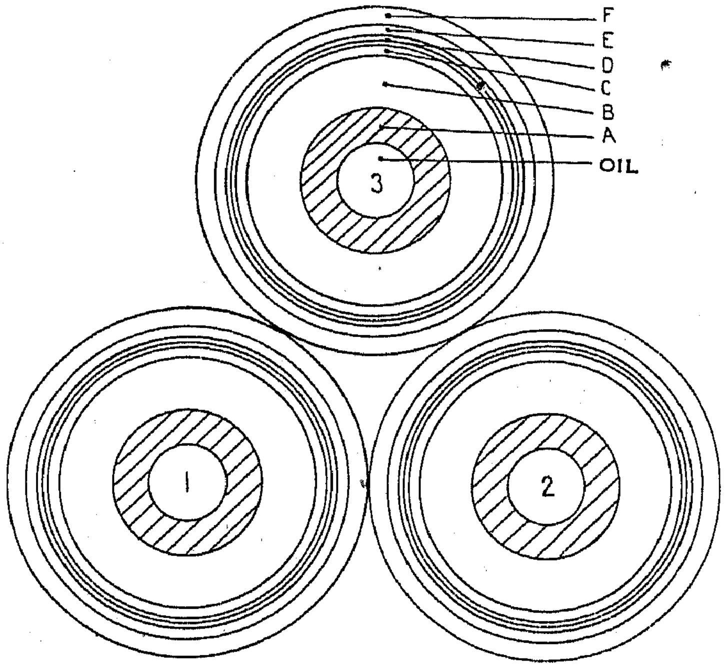

Fig. 14.—3-phase system of single-core p.i.d.l.s. oil-filled cables as laid in ground in trefoil.

A. Copper. B. Paper. C. Lead. D. Brass tape and paper.
E. Lead. F. Hessian.

The outer sheaths of the cables will be bonded together and to earth at each cable joint, so that it is obvious that, under sustained conditions for the given applied current in any cable section, there will be a constant current flowing in the cable sheath-to-sheath circuit, and the effective inductance experienced by the current in the cores will be the total inductance between the core conductors, i.e. that equivalent to twice the star reactance per phase. This will not be the case, however, whilst the sheath currents are passing through the transient stage required to attain this steady value, so that the effective inductance between the core conductors during this stage cannot be taken as twice the effective star inductance. Whilst it is possible to set up the differential equations governing these transient conditions, it has not been found possible to solve them: the approximate analysis given below appears, however, to lead to reliable results.

Let Fig. 15 represent any section of two of the cables in which, by reason of the sheath bonding, it is possible for circulating currents to flow in the sheath-to-sheath circuit. Consider that a current $i = At$ is flowing into Conductor 1, along the conductor, through the core-to-sheath capacitance and the earth bonds, and out through Conductor 2. This current is supplied from a high-impedance source, so that it is unaffected by the impedance of the system in which it is flowing. Time t is zero at the instant at which an applied current reaches the section of cable we are considering.

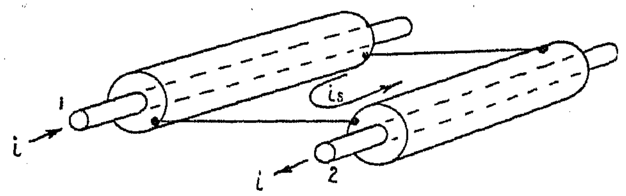

Fig. 15.—Representation of two cables of Fig. 14, showing circuit of sheath transients (i_s).

Now, considering the sheath-to-sheath circuit in which the current i_s is flowing, we have

$$M\frac{di}{dt} = L_s\frac{di_s}{dt} + 2R_s i_s$$

where L_s is the inductance of the sheath-to-sheath circuit per unit length, R_s is the resistance of each sheath per unit length, and M is the mutual inductance between the core-to-core and sheath-to-sheath circuits. We have, however,

$$i = At$$

and so
$$\frac{di}{dt} = A$$

Hence
$$i_s = \frac{MA}{2R_s}(1 - \epsilon^{-\frac{2R_s}{L_s}t})$$

The relation between core and sheath currents is shown in Fig. 5. Since the sheaths are concentric with the cores, $M = L_s$; and so, for small values of $(2R_s/L_s)t$, we can write $i_s = At$. That is, initially, a current equal and opposite to the core current is induced in each sheath. Over the short time during which this condition may be supposed to hold, the effective inductance experienced by the current i in the cores is $2L_C$, where L_C is the inductance between the core and the sheath of each cable. Over the same time the effective resistance per unit length is $2R_C + 2R_s$, where R_C is the resistance of each core per unit length. Over this short time, therefore, it would be legitimate to regard the system as one in which the current was applied to a system of resistance $(2R_C + 2R_s)$ per unit length, inductance $2L_C$ per unit length, and capacitance $C/2$ per unit length (C being the core-to-sheath capacitance of each cable). This does not, however, hold for a time sufficiently long for our purposes.

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* See Reference (6).

We may, nevertheless, proceed further on the same lines. We can, over the time in which we are interested, plot together i and i_s (see Fig. 5) and we may say that, over any sufficiently small interval of time,

$$i_s = Ki$$

where $$K = \frac{di_s}{dt}\frac{1}{A} \left(A \text{ being, of course, } \frac{di}{dt}\right)$$

Over any interval of time during which $i_s/i = K$, the effective inductance encountered by i is then

$$L_K = 2L_C + (1 - K)L_s$$

and the effective resistance is

$$R_K = 2R_C + 2KR_s$$

We can thus establish intervals of time $(t_0 - t_1)$, $(t_1 - t_2)$, $(t_2 - t_3)$, etc., during each of which the currents

$$i_{(t_0 - t_1)},\ i_{(t_1 - t_2)},\ i_{(t_2 - t_3)}$$

entering the system at the starting end will encounter the effective constants

$$R_{K_0}, L_{K_0}, C, R_{K_1}, L_{K_1}, C,$$

etc., throughout their travel along the system. The current entering the system during the time $(t_0 - t_1)$ is

$$i_{t_0 - t_1} = \Big[At\Big]_0^1$$

The current entering the system during the time $(t_{n-1} - t_n)$ is

$$i_{t_{(n-1)} - t_n} = \Big[A(t - t_{n-1}) + At_{n-1}1_{(n-1)}\Big]_{n-1}^n$$

Thus if the voltage appearing across the system terminals due to the application of a linear current $i = At$ to the system of constants R_K, L_K, C is

$$AF_1(R_K, L_K, C, t)$$

and the voltage due to application of the current At_n1 to the same system is

$$At_nF_0(R_K, L_K, C, t)$$

then the total voltage across the system terminals from time t_{n-1} to time t_n is

$$\begin{aligned}\Big[e\Big]_{n-1}^n = A\Big\{&F_1\big[R_{K_0}L_{K_0}Ct\big] + F_1\big[R_{K_1}L_{K_1}C(t - t_1)\big]\ldots\\
&+ F_1\big[R_{K_{(n-1)}}L_{K_{(n-1)}}C(t - t_{n-1})\big]\\
&- F_1\big[R_{K_0}L_{K_0}C(t - t_1)\big] - F_1\big[R_{K_1}L_{K_1}C(t - t_2)\big]\ldots\\
&- F_1\big[R_{K_{(n-2)}}L_{K_{(n-2)}}C(t - t_{n-1})\big]\\
&- t_1F_0\big[R_{K_0}L_{K_0}C(t - t_1)\big] - t_2F_0\big[(R_{K_1}L_{K_1}C(t - t_2)\big]\ldots\\
&- t_{n-1}F_0\big[R_{K_{(n-2)}}L_{K_{(n-2)}}C(t - t_{n-1})\big]\\
&+ t_1F_0\big[R_{K_1}L_{K_1}C(t - t_1)\big] + t_2F_0\big[R_{K_2}L_{K_2}C(t - t_2)\big]\ldots\\
&+ t_{n-1}F_0\big[R_{K_{(n-2)}}L_{K_{(n-2)}}C(t - t_{n-1})\big]\Big\}\end{aligned}$$

The process represented by the above expression can be put into words as follows: At time $t = 0$ we calculate the voltage resulting from the application of the current $i = At$ to the system of constants R_{K_0}, L_{K_0}, C. At time t_1 we apply to the system (R_{K_0}, L_{K_0}, C) a current $-At_11$ and a linear current $-A(t - t_1)$, and calculate the voltages at the system terminals. The sum of these voltages represents the voltage at the system terminals resulting from the application of a current which starts at zero, rises linearly till time t_1, and then drops to zero. This pulse of current travels throughout the system, all the time encountering the constants R_{K_0}, L_{K_0}, C, and does in fact give rise to a small voltage at the system terminals after the current in the external source has dropped to zero.

After time $t = t_1$ we further calculate the voltage arising on the application of a linear current $A(t - t_1)$ together with a current At_11 to the system of constants R_{K_1}, L_{K_1}, C, and again at $t = t_2$ we apply currents $-At_21$ and $-A(t - t_2)$ to the same system, at the same time applying $+At_21$ and $+A(t - t_2)$ to the system of constants R_{K_2}, L_{K_2}, C, and so on. Thus we calculate the voltage at the system terminals resulting from the application of a linear current, of which all the current entering during any interval of time, say, t_n to t_{n-1}, encounters the appropriate parameters R_K, L_K, C.

Fig. 6 shows the result of such a calculation, together with the comparable transient recorded by the restriking-voltage indicator, to which a voltage calibration is applied as described in Appendix I. The curves shown, regarded as inherent transients of restriking voltage, represent the voltage-rise at the rupture of 1 000 amperes r.m.s. at 50 cycles per sec., flowing in a 3-phase cable-run consisting of three 0·35-sq. in. single-core oil-filled p.i.d.l.s. 66-kV cables, each cable served with hessian and laid in trefoil with coverings touching. The calculation is carried out for 400 microseconds, and, on the theory here presented alone, should completely represent the transient on the cable system (which was 16⅓ miles long) over the first 295 microseconds, the fastest propagation velocity in the cable, on this theory, being $1{\cdot}11 \times 10^5$ miles per microsecond. In fact, voltages reflected from the far end of the cable appear somewhat earlier than this, as will be mentioned below.

In evaluating the resistances, inductances, etc., necessary for the above calculation, the inner and outer lead sheaths of each cable were treated as though they were electrically in parallel, i.e. all sheath currents were regarded as being uniformly distributed over the inner and outer sheaths. In calculating the core-to-sheath inductance of one cable, and the sheath-to-sheath inductances of the two cables, the inner and outer sheaths together were treated as a single cylinder in each case, the effect of the intersheath filling and the brass-tape armouring being neglected. No account was taken of eddy-current losses in the earth in which the cable was laid, a preliminary rough calculation having shown that these were likely to be unimportant.

Whilst the above treatment appears to be sufficiently accurate for the calculation of the slope of the first rise of voltage, it is not good enough for the precise calculation of the reflected waves returning from the far end of the cable, and hence for calculation of the peak value obtained by the restriking-voltage transient. The fastest propagation velocity given by the above theory is 111 000 miles per sec. (9 microsec. per mile); thus, for a cable $16\frac{1}{3}$ miles long, the front of the transient should continue to follow the same law for approximately 300 microseconds. Actually some result from the application of an impulse to one end of the cable must be able to travel along the cable with a velocity determined by the core-to-sheath capacitance and the inductance between the outermost element of the core and the innermost element of the sheath.

For the present cable this maximum velocity is 141 000 miles per sec. (7·1 microseconds per mile), the time required to traverse the cable and return being 232 microseconds. From an examination of the observed transient of Fig. 5 it will be seen that some alteration in the rate of change of the curvature of the transient does in fact appear to occur between 250 and 300 microseconds after the start. It is hoped to proceed shortly with an examination of the rather difficult problem of the influence of such "skin effects" as are here implied on the propagation velocity and distortion of waves travelling along the cables.

These phenomena are of considerable importance in determining the peak values to which the transients with which we are concerned can rise.

APPENDIX IV

The Front of the Restriking-voltage Transient, and the Effective Surge Impedance of the Cable System, on the Interruption of a Phase-to-earth Short-circuit

No record was taken using this connection, but the calculation is made here because it enters into a case dealt with in Appendix V.

The system to which the current $i = At$ must be considered applied in calculating the front of the transient is shown in Fig. 7. We may consider that in the first instance the current $i = At$ all flows in the core and sheath of Cable 1 and that currents i_2, i_3 are induced in the circuits S_1S_2, S_1S_3. It will be clear that negligible current will be set up in Conductors 2 and 3, and also that $i_2 = i_3$, since Sheaths 2 and 3 are symmetrically disposed with respect to Sheath 1. The system can thus be regarded as a distributed circuit of the form shown in Fig. 16. The sheath transients may now be found in the manner adopted in Appendix III, in the case of the interruption of the phase-to-phase short-circuit.

Consider that a current $i = At$ is applied to System 1, and that the front of the current wave reaching any section remains of the form At. Referring to Fig. 16, let R_1 = resistance of Sheath 1, R_2 = resistance of Sheath 2, R_3 = resistance of Sheath 3, L_2 = inductance of path "Sheath 1 to Sheath 2" $= L_{SS}$, L_3 = inductance of path "Sheath 1 to Sheath 3" $= L_{SS}$, M = mutual inductance between circuits Sheath 1 to Sheath 2 and Sheath 1 to Sheath 3, L_{CS} = self-inductance between core and sheath of any one cable.

Then we have

$$R_1(i - i_2 - i_3) = i_2R_2 + i_2pL_2 + i_3pM$$

$$= i_3R_3 + i_3pL_3 + i_2pM$$

Now $\quad i_2 = i_3, \quad R_2 = R_3, \quad L_2 = L_3 = L_{SS},$

so that $\quad R_1(i - 2i_2) = i_2(R_2 + pL_{SS} + pM)$

and
$$\frac{i}{i_2} = \frac{R_2 + 2R_1 + pL_{SS} + pM}{R_1}$$

But
$$R_1 = R_2 = R_3 = R \text{ (say)}$$

and
$$M = \frac{L_2}{2} = \frac{L_3}{2} = \frac{L_{SS}}{2}$$

So that
$$\frac{i}{i_2} = \frac{3R + (3/2)pL_{SS}}{R} = \frac{3}{R}\left(R + p\frac{L_{SS}}{2}\right)$$

and
$$i_2 = \frac{iR}{3(R + pL_{SS}/2)}$$

But
$$i = At = \frac{A}{p}1$$

So that
$$i_2 = \frac{AR}{3p(R + pL_{SS}/2)}1$$

$$= \frac{A}{3}\left[t - \frac{L_{SS}}{2R}(1 - \epsilon^{-2Rt/L_{SS}})\right]$$

Here $i_2 = i_3$ is initially zero, so that the total current in Sheath 1 is equal to the current in Conductor 1, and the surge impedance initially encountered is that between one conductor and its sheath. The currents in the sheath-to-sheath circuits, however, fall off fairly rapidly, increasing the effective inductance of the system and decreasing its effective resistance.

We may calculate the effective inductance and resistance of the system at any time after the arrival of the current wave-front at that point as follows: Let the current in Sheath 1 at any time be

$$i - 2i_2 = Ki$$

The total rate of dissipation of energy per unit length is then

$$K^2i^2R + 2R\left(\frac{1-K}{2}\right)^2 I^2$$

$$= I^2R\left(\frac{3}{2}K^2 - K + \frac{1}{2}\right)$$

and the effective resistance per unit length is given by

$$R\left(K^2\frac{3}{2} - K + \frac{1}{2}\right)$$

The total linkages per unit length are

$$iL_{CS} + 2i_2L$$

$$= iL_{CS} + (1 - K)iL$$

The effective inductance per unit length is thus

$$L_{CS} + (1 - K)L$$

We can now proceed to evaluate K and calculate the transient of restriking voltage, as was done in Appendix III, for the phase-to-phase case. Curve (i) in Fig. 8 shows the result of such a calculation for the present cable system.

To find out the importance of the effect of the currents in the sheaths of the two unfaulted cables, the transient which would occur if the sheaths of the two unfaulted cables were completely isolated was also calculated: this is shown in Curve (ii), Fig. 8. It will be seen that the effect of the two additional cable-sheaths in parallel has been to increase the effective surge impedance above 300 microseconds by about 25 %. Although it appears at first sight surprising that the effective surge impedance should be increased by the addition of parallel paths to the circuit, this can be explained by the argument that the increase of inductance per unit length without any corresponding increase in capacitance raises the effective surge impedance to a greater extent than the reduction in resistance of the system per unit length diminishes it.

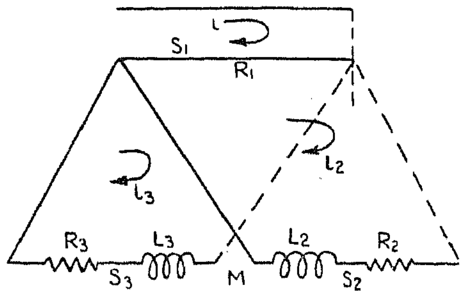


Fig. 16.—Equivalent distributed circuit for transients at interruption of phase-to-earth short-circuit (effect of cores of unfaulted cables neglected, see Appendix IV).

APPENDIX V

Approximations to the Front of the Restriking-voltage Transient and the Effective Surge Impedance of the System, on the Interruption of a Phase-to-phase-to-earth Short-circuit

The system to which the current $i = At$ must be considered applied in calculating the front of the restriking-voltage transient in this case is shown in Fig. 2(ii). It will be seen that this system is identical with that of the phase-to-earth case (Fig. 7), except for the connection of Core 1 to the earthed system. The differential equations governing the phenomena arising in this instance have so far proved insoluble, but we may proceed as follows:—

We have seen in Appendix IV the effect of additional sheaths in parallel with the faulted cable on the effective surge impedance on a phase-to-earth fault. If we calculate separately the effect of an additional core, we can estimate the net effect of two additional sheaths plus one additional core.

The effect of an additional core may be calculated in the following way: Consider the system of Fig. 17; this is electrically identical with that of Fig. 16 if

$$R_a = R_d = R_c,\ L_{a-b} = L_{b-d} = L_{CS},\ R_b = \tfrac{1}{2}R_S$$

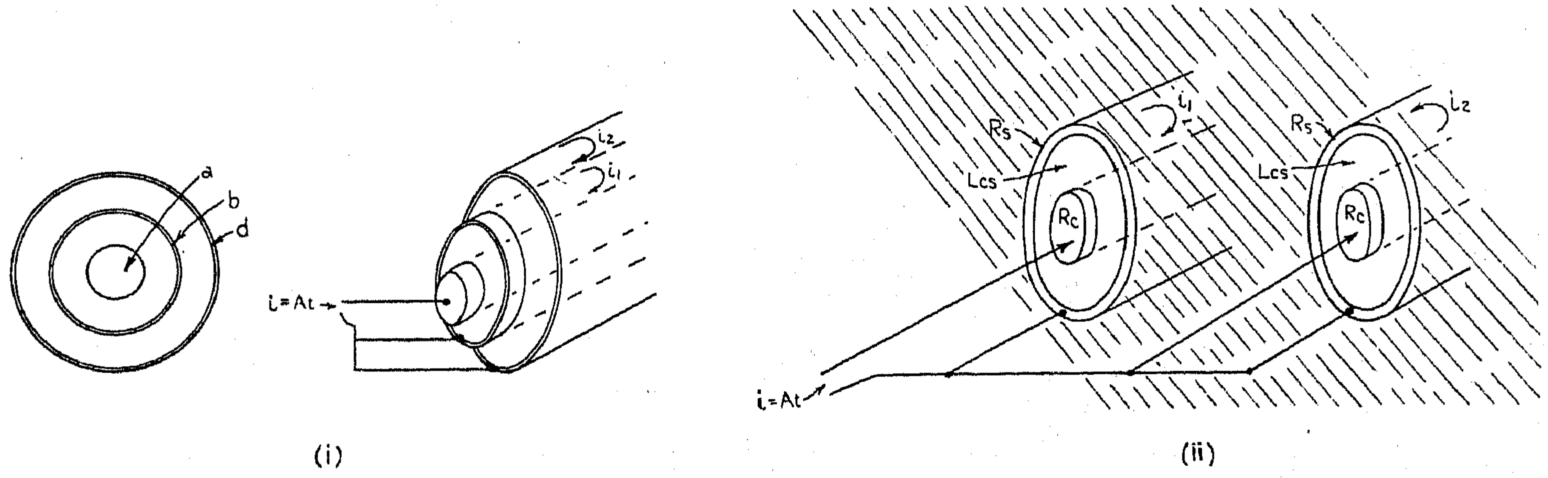
and if the shaded region in Fig. 17(ii) is supposed to have zero permeability, and zero conductivity in the direction parallel to the conductors, with infinite conductivity in the plane at right angles to the direction of the conductors. We can now calculate the voltage at the end of such a system on the application of a current $i = At$ to the system in the appropriate connection for the interruption of a phase-to-phase-to-earth fault. Consider the system of Fig. 17(ii). We have, for a cable considered infinite,

$$(1)\ \begin{cases} \dfrac{\delta i_1}{\delta x} = -\ e_1pC_1 + e_1G_1 \\[2ex] \dfrac{\delta i_2}{\delta x} = -\ e_2pC_2 + e_2G_2 \end{cases}$$

$$(2)\ \begin{cases} \dfrac{\delta e_1}{\delta x} = -\left\{i_1(R_1 + pL_1) - i_2M\right\} \\[2ex] \dfrac{\delta e_2}{\delta x} = -\left\{i_2(R_2 + pL_2) - i_1M\right\} \end{cases}$$

where C_1, C_2, G_1, G_2, are the capacitance and leakage conductance respectively, R_1 and R_2 are the resistances per unit length of Cables 1 and 2, L_1 and L_2 the core-to-sheath inductances, and M the mutual impedance between the two cables. Writing—

$$Z_1 = R_1 + pL_1, \text{ etc.}$$
$$Y_1 = G_1 + pC_1, \text{ etc.}$$



(i)

(ii)

Fig. 17.—Approximate equivalent system for calculation of restriking-voltage transient at interruption of first phase of phase-to-phase-to-earth short-circuit (see Appendix V).

and differentiating again, we get, on rearranging,

$$(3)\quad \begin{cases} 0 = e_1\left(Z_1Y_1 - \dfrac{\delta^2}{\delta x^2}\right) - e_2(MY_2) \\ 0 = e_1(MY_1) + e_2\left(Z_2Y_2 - \dfrac{\delta^2}{\delta x^2}\right) \end{cases}$$

Following the method of Bewley,* we may say that solving equation (3) for any value of e gives a fraction of which the numerator is zero since it is a determinant containing a column of zeros. For any solution to exist, therefore, the denominator must also be zero (on the assumption that the indeterminate so formed will have a finite value). Thus

$$(4)\quad \begin{vmatrix} \left(Z_1Y_1 - \dfrac{\delta^2}{\delta x^2}\right) & - MY_2 \\ - MY_1 & \left(Z_2Y_2 - \dfrac{\delta^2}{\delta x^2}\right) \end{vmatrix} = 0$$

and since, for identical cables, $Z_1Y_1 = Z_2Y_2 = ZY$ (say), it follows that

$$(5)\quad \left[\left(ZY - \frac{\delta^2}{\delta x^2}\right)^2 - M^2Y^2\right] = 0$$

and

$$(6)\quad \left(ZY - MY - \frac{\delta^2}{\delta x^2}\right)\left(ZY + MY - \frac{\delta^2}{\delta x^2}\right) = 0$$

This differential equation must apply to any of the variables eliminated from equation (3). Thus, writing e in the meantime for e_1 or e_2, we have

$$(7)\quad \frac{\delta^2 e}{\delta x^2} = (ZY - MY)e = \alpha^2 e \text{ (say)}$$

or

$$(8)\quad \frac{\delta^2 e}{\delta x^2} = (ZY + MY)e = \beta^2 e \text{ (say)}$$

That is,

$$(9)\quad e = K_1\epsilon^{-\alpha x} + K_2\epsilon^{-\beta x}$$

or

$$e_1 = P\epsilon^{-\alpha x} + Q\epsilon^{-\beta x}$$
$$e_2 = R\epsilon^{-\alpha x} + S\epsilon^{-\beta x}$$

(terms with positive exponential indices being neglected, since we are dealing with an infinite cable). The waves represented by the terms $\epsilon^{-\alpha x}$, $\epsilon^{-\beta x}$, must individually obey the constraints expressed by the differential equations.

We have, first, since $e_2 = 0$ at $x = 0$,

$$R = - S$$

Taking now the components in αx, and putting $G = 0$ (since leakage conductance is usually negligible in systems of the type here discussed),

$$e_{1\alpha} = P\epsilon^{-\alpha x}$$

$$(10)\quad i_{1\alpha} = - pC\int e_{1\alpha}dx = \frac{pCP\epsilon^{-\alpha x}}{\alpha}$$

$$(11)\quad e_{2\alpha} = R\epsilon^{-\alpha x}$$

$$(12)\quad i_{2\alpha} = \frac{pCR\epsilon^{-\alpha x}}{\alpha}$$

But $\dfrac{\delta e_{1\alpha}}{\delta x} = - (i_{1\alpha}Z - i_{2\alpha}M)$

So $- \alpha P\epsilon^{-\alpha x} = \left(- \dfrac{pCZP}{\alpha} + \dfrac{pCRM}{\alpha}\right)\epsilon^{-\alpha x}$

or

$$(13)\quad R = P\frac{pCZ - \alpha^2}{pCM}$$

Thus

$$(14)\quad e_{1\alpha} = P\epsilon^{-\alpha x}$$

$$(15)\quad e_{2\alpha} = \frac{P}{pCM}(pCZ - \alpha^2)\epsilon^{-\alpha x}$$

Similarly

$$(16)\quad e_{1\beta} = Q\epsilon^{-\beta x}$$

$$(17)\quad e_{2\beta} = Q\frac{1}{pCM}(pCZ - \beta^2)\epsilon^{-\beta x}$$

But $e_2 = 0$ at $x = 0$, and thus

$$(e_{2\alpha})_0 = - (e_{2\beta})_0$$

and $\dfrac{Q}{pCM}(pCZ - \beta^2) = \dfrac{-P}{pCM}(pCZ - \alpha^2)$

Inserting values for α^2, β^2, from (7) and (8), we have

$$(18)\quad Q = P$$

Thus

$$(19)\quad e_1 = P(\epsilon^{-\alpha x} + \epsilon^{-\beta x})$$

$$(20)\quad e_2 = R(\epsilon^{-\alpha x} - \epsilon^{-\beta x})$$

Again, we have

$$(21)\quad i_1 = - pC\int e_1 dx = + pCP\left(\frac{\epsilon^{-\alpha x}}{\alpha} + \frac{\epsilon^{-\beta x}}{\beta}\right)$$

and similarly

$$(22)\quad i_2 = + pCR\left(\frac{\epsilon^{-\alpha x}}{\alpha} - \frac{\epsilon^{-\beta x}}{\beta}\right)$$

But, from (2), $\dfrac{\delta e_1}{\delta x} = - (i_1Z - i_2M)$

$$= - pCPZ\left(\frac{\epsilon^{-\alpha x}}{\alpha} + \frac{\epsilon^{-\beta x}}{\beta}\right) + pRMC\left(\frac{\epsilon^{-\alpha x}}{\alpha} - \frac{\epsilon^{-\beta x}}{\beta}\right)$$

This again must apply to components α, β, taken separately, and so

$$(23)\quad P\left(\frac{pCZ}{\alpha} - \alpha\right) = \frac{pCRM}{\alpha}$$

and hence, substituting for α from (7), we get

$$(24)\quad P = R$$

Thus

$$(25)\quad e_1 = P(\epsilon^{-\alpha x} + \epsilon^{-\beta x})$$

$$(26)\quad e_2 = P(\epsilon^{-\alpha x} - \epsilon^{-\beta x})$$

and

$$(27)\quad i_1 = - pC\int e_1 dx = pCP\left(\frac{\epsilon^{-\alpha x}}{\alpha} + \frac{\epsilon^{-\beta x}}{\beta}\right)$$

Now, for linear current applied,

$$(28)\quad (i_1)x = 0 = Kt = \frac{K}{p}1$$

So that $\dfrac{K}{p}1 = pCP\left(\dfrac{1}{\alpha} + \dfrac{1}{\beta}\right)$

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* See Reference (5).

and

$$(29)\quad P = \frac{1}{C}\frac{K}{p^2}\frac{\alpha\beta}{\alpha+\beta}$$

Thus, for the condition stated in (28),

$$(e_1)_{x=0} = 2P = \frac{2K}{p^2}\frac{1}{C}\frac{\alpha\beta}{\alpha+\beta}$$

where α, β, are both irrational.

Rationalizing the expression on the right-hand side of this equation and substituting for α, β, from (3) and (4),

$$(30)\quad (e_1)_{x=0} = \frac{K}{Cp^2} \times \left[\frac{(Z-M)\sqrt{(ZY+MY)}-(Z+M)\sqrt{(ZY-MY)}}{-M}\right]$$

We may put

$$M = R_S, \quad Z = R + pL, \quad Y = pC,$$

where

$$R = R_C + R_S$$

Then

$$Z - M = R_C + pL$$

$$Z + M = R_C + 2R_S + pL, \text{ or (say) } = R_T + pL$$

and

$$(31)\quad (e_1)_{x=0} = -\frac{K}{Cp^2}(\sqrt{pC}) \times \frac{[(R_C+pL)\sqrt{(R_T+pL)}-(R_T+pL)\sqrt{(R_C+pL)}]}{R_S}$$

Now

$$\sqrt{(R_T + pL)} = \sqrt{(pL)}\sqrt{\left(1 + \frac{R_T}{pL}\right)}$$

$$= \sqrt{(pL)}\left(1 + \frac{R_T}{2pL} - \frac{R_T^2}{2^2 \,.\, 2!p^2L^2} + \frac{3R_T^3}{2^3 \,.\, 2!p^3L^3}\cdots\right)$$

$$= \sqrt{(pL)}F(\sigma_T, p) \text{ say, where } \sigma_T = R_T/L.$$

Similarly

$$\sqrt{(R_C + pL)} = \sqrt{(pL)}F(\sigma_C, p), \text{ where } \sigma_C = R_C/L.$$

Hence

$$(e_1)_{x=0} = \frac{-K\sqrt{(pC)}}{p^2CR_S} \times [(R_C+pL)\sqrt{(pL)}F(\sigma_T,p)-(R_T+pL)\sqrt{(pL)}F(\sigma_C,p)]$$

$$(32)\quad = \frac{-K}{R_S}\sqrt{\left(\frac{L}{C}\right)} \times \left[R_C\frac{F(\sigma_T,p)}{p}+LF(\sigma_T,p)-\frac{R_TF(\sigma_C,p)}{p}-LF(\sigma_C,p)\right]$$

where

$$F(\sigma,p) = \left(1 + \frac{\sigma}{2p} - \frac{\sigma^2}{2^2 \,.\, 2!p^2} + \frac{3\sigma^3}{2^3 \,.\, 3!p^3} - \ldots\right)$$

$$= \left(1 + \frac{\sigma t}{2} - \frac{\sigma^2t^2}{2^2(2!)^2} + \frac{3\sigma^3t^3}{2^3(3!)^2} - \ldots\right)$$

and

$$\frac{F(\sigma,p)}{p} = \left(t + \frac{\sigma t^2}{2 \,.\, 2!} - \frac{\sigma^2t^3}{2^2 \,.\, 2! \,.\, 3!} + \frac{3\sigma^3t^4}{2^3 \,.\, 3! \,.\, 4!}\cdots\right)$$

This expression for $(e_1)_{x=0}$, i.e. the voltage at the starting end of the cable has been used to calculate the transient shown in Fig. 9, Curve (i).

Now the voltage arising on the application of the same current to a system exactly as that of Fig. 7(i) but with the outer conductor removed, can be simply calculated in the manner described in Appendix II. This has been plotted in Fig. 9, Curve (ii). It will be seen that the effect of the second conductor on the effective impedance is negligible.

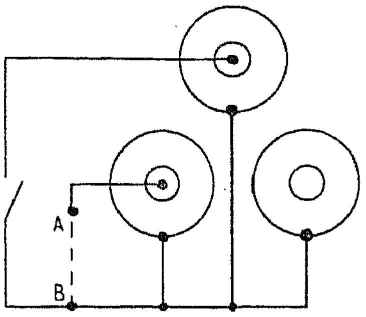

Fig. 18.—Approximate equivalent system for calculating transients at opening of first phase of phase-to-phase-to-earth short-circuit (see Appendix V).

We may then extend the argument and say that opening or closing of the link A–B on a system such as that of Fig. 18 should make negligible difference to the transient we are dealing with, and consequently the transient voltage per 1 000 amperes of fault-current arc at the interruption of the first phase to clear of a phase-to-phase-to-earth fault should be very much the same as the transient voltage per 1 000 amperes at the interruption of a phase-to-earth fault. The latter has been calculated as described in Appendix IV; it is replotted in Fig. 9, Curve (iii), for purposes of comparison.

The observed transient per 1 000 amperes, for the connection appropriate to the interruption of the first phase to clear on a phase-to-phase-to-earth short-circuit, has also been plotted [Fig. 9, Curve (iv)], and it will be seen that all things considered the prediction is justified that Curves (iii) and (iv) should agree approximately.

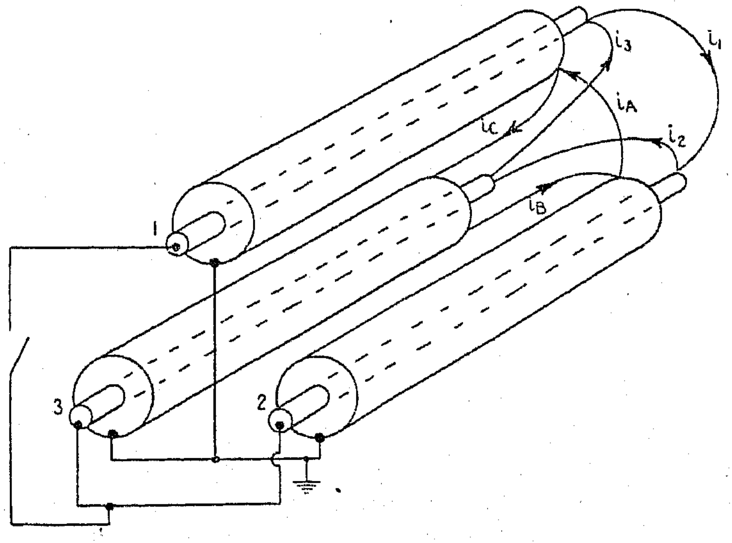

Fig. 19.—System at opening of first phase of 3-phase short-circuit (see Appendix VI).

APPENDIX VI

The Front of the Restriking-voltage Transient, and the Effective Surge Impedance of the System, at the Opening of the First Phase of a 3-phase Short-circuit

The system to which the current $i = At$ must be considered applied in this case is shown in Fig. 2(iii). From consideration of the sheath circulating-currents, as indicated in Fig. 19, it can be shown that the voltage arising across the terminals 1 and 2 + 3, on the application of a current $i = At$ between these terminals, is $\frac{3}{4}$ of the voltage which would arise between, say, Conductor 1 and Conductor 2 if Conductor 3 were isolated and the current applied between Conductors 1 + 2. This latter case has already been treated in Appendix III.

Calculation of the front of the restriking-voltage transient per 1 000 amperes of fault current on this basis gives the result which is shown in Fig. 10 along with the observed transient. It will be seen that the agreement is quite good.

MODERN ELECTRIC DISCHARGE LAMPS*

By G. G. ISAACS, B.Sc., Graduate.

(ABSTRACT *of paper read before the* LONDON STUDENTS' SECTION, 17*th December*, 1937.)

INTRODUCTION

A note which Faraday made a century ago, in his diary, is of interest in relation to the production of light by means of an electric discharge. In March, 1838, he wrote: "Endeavoured to obtain luminous discharge between two electrics, one negative, the other positive. This not so easy."

Limitations of space prohibit a description of the theories and experiments of the early days in this work, and it is intended here to deal only with modern forms of electric discharge lamp.

High-voltage discharge tubes have long been established for advertising and display purposes. More recently, low-voltage discharge lamps, which operate on ordinary mains supplies (200 to 260 volts), have been developed and their use both for industrial and for street lighting has increased very rapidly over the last 5 years.† (In Great Britain there are now about 50 000 of these lamps in use for street lighting alone.) The most recent developments, however, have resulted in units for interior lighting, and in special lamps for projection purposes.

In this paper the more important types of electric discharge lamp are described and an attempt is made to indicate how both theoretical and experimental research are employed in their design.

FACTORS INFLUENCING LAMP DESIGN

The theory of the operation of electric discharge lamps may be summarized as follows:—

(1) Light is produced by the interaction of electrons and atoms, and it may be emitted either unchanged, or modified by falling on luminescent materials.

(2) The electrical characteristics of a discharge are such that a current-limiting device (e.g. a choke coil or resistor) must be included in the circuit.

The purpose for which the lamp is required is the main factor governing a decision with regard to the following characteristics: (i) The colour of the light. (ii) The dimensions of the light source. (iii) The intrinsic brightness of the source. (iv) The electrical characteristics (for example, whether a.c. or d.c. supply).

In producing a lamp with the characteristics thus determined, the designer has certain variables under his control, namely the nature of the gas or vapour filling the lamp, the gas pressure, and the current through the lamp. A combination of theory and experimental results will indicate the optimum values of these variables, and it remains to construct a lamp which can be operated under these conditions, using the materials available. The design of the electrical equipment to obtain the desired running and starting conditions is, of course, of equal importance.

The majority of the lamps operate on alternating current with a lamp power-factor of about 0·9.

HIGH-VOLTAGE TUBES

As the characteristics of these tubes are fairly well known they will be mentioned here only in connection with luminescence.†

It has been found that, by coating the inner wall of a cold-cathode tube with a luminescent powder, ultraviolet light from the discharge may be converted into visible light. The use of suitable powders not only enables a wide range of colours to be obtained but also in many cases raises the luminous efficiency (see Table).

The main applications of such tubes are: (1) Advertising and display. (2) Interior lighting.

HOT-CATHODE LAMPS

For purposes such as floodlighting, a source of greater intrinsic brightness than the normal cold-cathode tube is desirable; this may be obtained by increasing the number of light-producing "impacts" by increasing the current density. Sputtering at the electrodes is avoided

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* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

† C. C. PATERSON: *Illuminating Engineer* (London), 1932, vol. 25, p. 309.

† J. W. RYDE: *Transactions of the Illuminating Engineering Society* (London), 1938, vol. 3, p. 114; J. T. RANDALL: *G.E.C. Journal*, 1937, vol. 8, p. 103.

Table

HIGH-VOLTAGE FLUORESCENT TUBES

Gas or vapour filling	Luminous powder used	Resultant colour	Luminous efficiency of tube, in lumens per watt (average values)	Surface brightness of tube, in candles per cm^2
Mercury (with argon and/or neon starting gas)	None	Pale blue	5	0·05
	Zinc orthosilicate	Bright green	50–60	0·40
	Zinc meso-disilicate	Yellowish white	25	0·18
	Zinc-beryllium silicates (various)	Pink to cream-white	30–40	0·26
	Calcium tungstate	Deep blue	15	0·11
	Magnesium tungstate	Light blue	30	0·22
Neon	None	Orange-red	15	0·14
	Zinc orthosilicate	Yellow	22	0·19
	Calcium tungstate	Pink	15	0·14

The figures given refer to tubes of length 2·7 m., diameter 15–20 mm., and current 35–60 mA.

by using " hot cathodes," i.e. tungsten-wire spirals with a filling or core of active material.

Lamps of this type include hot-cathode neon and mercury floodlights, as well as mercury and sodium lamps for street lighting or floodlighting.

HIGH-PRESSURE MERCURY-VAPOUR LAMPS

The best-known member of this series of lamps* consists of a tube of hard glass, containing a rare gas at a few millimetres' pressure, and a small quantity of mercury. The discharge takes place between electrodes sealed through the glass at each end of the tube and heated only by the discharge. In normal operation the light source is a narrow column down the centre of the tube. The principal applications of these lamps are to street and industrial lighting, for which purposes a high luminous efficiency is of paramount importance and, as a consideration of the curve relating efficiency and pressure shows, a high pressure of mercury vapour is desirable.

In cases where it is necessary, colour correction can be applied by including small quantities of cadmium and zinc in the lamp and coating the outer jacket with a luminescent powder.

Research shows that, to construct a lamp of smaller wattage without an appreciable loss in efficiency, the lamp loading (i.e. wattage per centimetre of arc length) and the pressure must be increased. This has been made possible by the use of quartz for the lamp envelope and by improvements in electrode design. A large number of 80-watt and 125-watt quartz lamps are already in service. Thus, mercury-vapour lamps are now manufactured in sizes from 80 to 400 watts, to operate on supplies of 200–260 volts (a.c.), each with an efficiency about 3 times that of gas-filled tungsten lamps of equivalent wattage, and with an average life of 1 500 hours.

HIGH-BRIGHTNESS LAMPS

For projection purposes a source of extra-high brightness is required. This implies increasing the luminous output without increasing the size of the light source, and can be accomplished in a mercury-vapour lamp by increasing the wattage per centimetre of arc length and at the same time increasing the voltage per centimetre. The latter factor causes the constriction of the arc to increase, so that the light source remains small. The water-cooled quartz lamp operates under these conditions; e.g. 500 watts may be dissipated in a lamp of arc length $\frac{1}{2}$ in., with voltage 400 volts, to obtain a brightness of about 30 000 candles per cm^2, which is approximately twice the brightness of an ordinary 5-ampere carbon arc.

The conditions for high brightness may also be realized in a lamp without water cooling. Either direct or alternating current may be used to operate this type of lamp, which is still in the development stage.

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* J. W. RYDE: *G.E.C. Journal*, 1933, vol. 4, p. 199, and *Journal of the Royal Society of Arts*, 1934, vol. 82, p. 623; also G. H. WILSON, E. L. DAMANT, and J. M. WALDRAM: *Journal I.E.E.*, 1936, vol. 79, p. 241.

THE ELECTRIC STRENGTH OF AIR AT HIGH FREQUENCIES*

By E. W. SEWARD, B.Eng., Ph.D., Graduate.†

(*Paper first received* 20*th July*, 1937, *and in final form* 3*rd November*, 1938.)

SUMMARY

The paper describes a series of experiments on the electrical breakdown strength of air under sinusoidal voltage conditions over a frequency range from 50 to 900 kc./sec. It is shown that with frequencies of the order of 200–1 000 kc./sec. there is a noticeable reduction in the breakdown voltage between spherical electrodes one of which is insulated and the other earthed, the reduction becoming more marked as the frequency is increased. A modification of Townsend's theory,‡ based on a consideration of the ionization conditions prior to breakdown, is suggested, which explains the reduction in the electric strength of a sphere-gap at the higher frequencies.

INTRODUCTION

In the past, various investigators have noticed that the electric strength of air between spheres is reduced as the frequency of the applied voltage is increased.§ F. W. Peek‖ states that at high frequencies the breakdown voltage may depend upon some function of the frequency. No experimental evidence is produced, however, to support this statement.

F. Miseré,¶ working with a symmetrical sphere-gap having two insulated electrodes, carried out breakdown tests over a frequency range from 200 to 1 000 kc./sec. His results show a reduction of about 15 % in the breakdown voltage at the highest frequency (995 kc./sec.) compared with the corresponding figure at 50 cycles per sec. This is consistent with the experimental results given in the present paper, though the actual figures are not strictly comparable on account of the different earthing arrangements employed.

Townsend, who investigated the mechanism of breakdown at power frequency, evolved a theory connecting sparkover with corona. The theory is based upon the assumption of a constant electric strength of 30 kV per cm. for air under uniform-field conditions. In the case of non-uniform-field conditions, however, e.g. the sphere-gap, Russell has shown by calculation from observed results that the stress at the electrode surface must exceed 30 kV per cm. before breakdown can occur.** Townsend makes the following assumptions: (1) Ionization by collision occurs from the surface of the corona-forming electrode to a surface where the stress becomes equal to 30 kV per cm. (2) Between this electrode surface and the surface so defined a spark discharge takes place.

The experimental equations of Peek and Russell,†† for determining the relation between breakdown voltage and gap spacing for spherical electrodes at power frequency, are both consistent with these assumptions. It is shown later in the paper that, with slight modifications, this theory can be used to explain the reduction in the electric strength of a sphere-gap, as the frequency is increased, throughout the range under discussion.

DESCRIPTION OF APPARATUS

The apparatus employed for generating the high-frequency voltage consisted of a valve-driven power amplifier coupled inductively to a tuned output circuit.

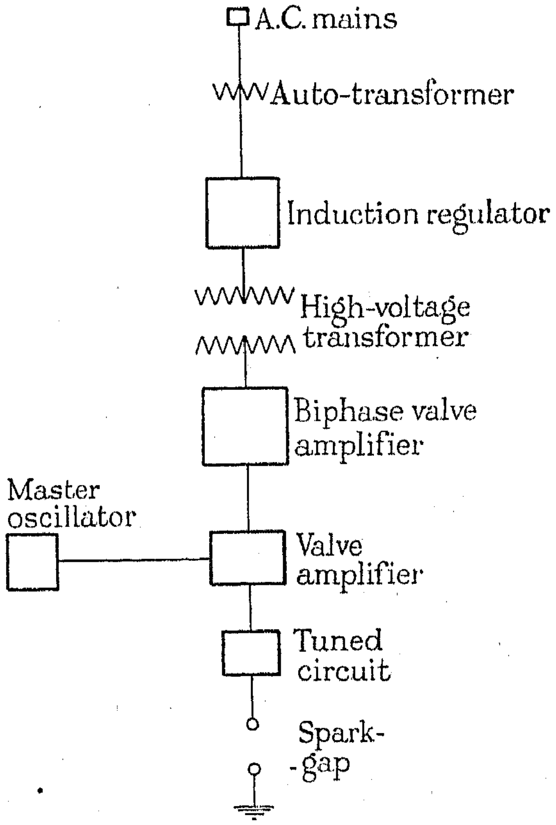

Fig. 1

This latter circuit contained the electrode gap across which the test voltages were applied.

A tuned circuit was used for the output stage, in order to avoid distortion of the voltage wave-form during experiments in which brush discharge preceded the actual breakdown. With this arrangement the harmonics generated by brush discharge are suppressed, owing to the large impedance of the test circuit to frequencies other than the resonant frequency.

The d.c. anode supply for the power amplifier was obtained from a biphase valve rectifier driven from the a.c. mains through a high-voltage transformer. An auto-transformer and induction regulator were included in the

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Instituton not later than one month after publication of the paper to which they relate.

[†] Liverpool University (now with Royal Air Force).

[‡] See Bibliography (1).

[§] *Ibid.*, (2).

[‖] *Ibid.*, (3).

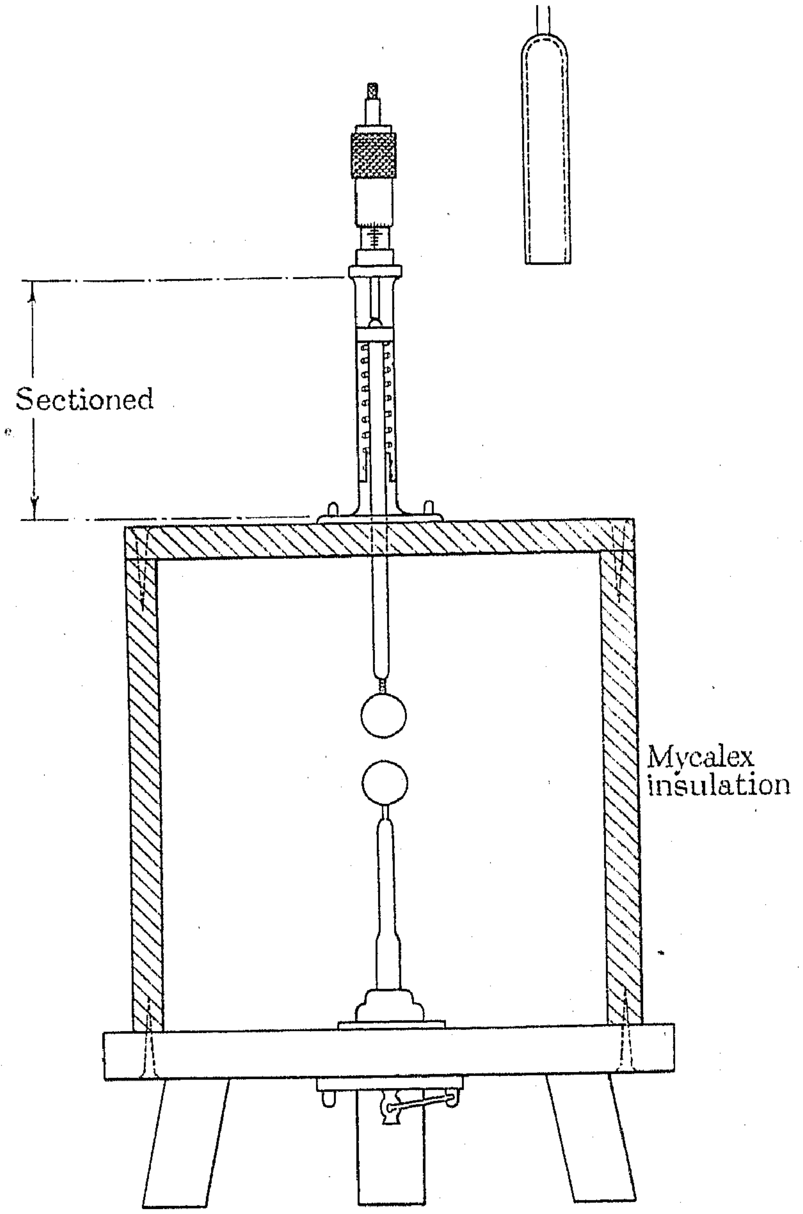
[¶] *Ibid.*, (4).

[**] *Ibid.*, (5).

[††] *Ibid.*, (5).

primary circuit of this transformer in order to obtain a steady rate of change of the voltage applied to the anode of the amplifying valve. This arrangement provides smooth control of the output voltage, as the magnitude of the latter is determined by the d.c. voltage at the valve anode. A line diagram of the circuit is shown in Fig. 1.

The test gap was constructed with mycalex insulation, the lower electrode, which was at earth potential, being fixed, while the upper insulated electrode was moved by a micrometer screw-gauge, thus enabling very accurate measurements of the gap setting to be made. A sectional view of the test gap is shown in Fig. 2.



Scale: ½ full size.

Fig. 2

As it is necessary to avoid frequency variations throughout the tests, the frequency of the applied voltage was checked at regular intervals by means of a calibrated heterodyne oscillator.

VOLTAGE MEASUREMENT

Voltage measurements were carried out by means of an electrostatic voltmeter in conjunction with a capacitance potential-divider. This arrangement was calibrated at power frequency by means of a high-voltage transformer, the step-up ratio of which had been accurately determined. The divider gives voltage measurements independent of frequency over the frequency range under consideration.*

SOURCES OF ERROR

The figures given in the paper were obtained with a rate of rise of test voltage of approximately 1 kV per sec. A more rapid rate of increase of applied voltage is liable to cause errors of reading of the electrostatic voltmeter, owing to the relatively slow response of this instrument.

Large variations in breakdown voltage may be observed in the presence of fibre and dust particles, and it is necessary to take precautions so as to avoid this source of error. When a potential difference is applied between the electrodes, these fibre and dust particles are drawn into the gap by electrostatic attraction, thus forming partial conducting bridges which lessen the effective gap length and cause breakdown to take place at reduced voltages. With large values of electrode spacing the errors due to this cause are not very important, but with small spacings they may introduce a large percentage error in the measured breakdown voltage.

The proper preparation of the test electrodes is another important factor in the elimination of errors. It has been found that the most consistent results are obtained with clean smooth surfaces, the values of the breakdown voltage being unreliable when visible pitting of the electrodes has taken place. It is not necessary, however, to work with polished mirror surfaces.†

TEST RESULTS

Test results have been obtained with frequencies of 50 cycles per sec., 109 kc./sec., 600 kc./sec., and 900 kc./sec., in the case of spherical steel electrodes of 5 mm. diameter, and with frequencies of 50 cycles per sec. and 600 kc./sec. in the case of 14-mm. diameter spheres. These results are shown in Fig. 3.

THEORY OF BREAKDOWN OF SPHERE-GAP IN AIR

The results given in Fig. 3 show that the voltage necessary to cause sparkover on any gap length decreases as the frequency of the applied voltage increases. This effect can be explained from a consideration of the ionization conditions prior to actual breakdown.

Consider a sphere-gap of which one electrode is earthed while the potential of the other is increasing positively, the maximum applied voltage being just sufficient to cause breakdown at 50 cycles per sec. When the voltage on the unearthed electrode attains a value such as that represented by PQ in Fig. 4, ionization by collision commences, and continues while the voltage is in excess of this value. During the remainder of this half-cycle, electrons will be attracted to and neutralized at the surface of the unearthed electrode A, while the positive ions, which possess a much lower mobility than the electrons, are repelled and form a space charge C near the surface of the earthed electrode B, as shown in Fig. 5(*a*). When the voltage of the unearthed electrode passes through zero and begins to increase on the negative half-cycle, the positive space-charge C is attracted by the unearthed electrode A, thus negative charge on the

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* See Bibliography, (6).

† *Ibid.*, (7).

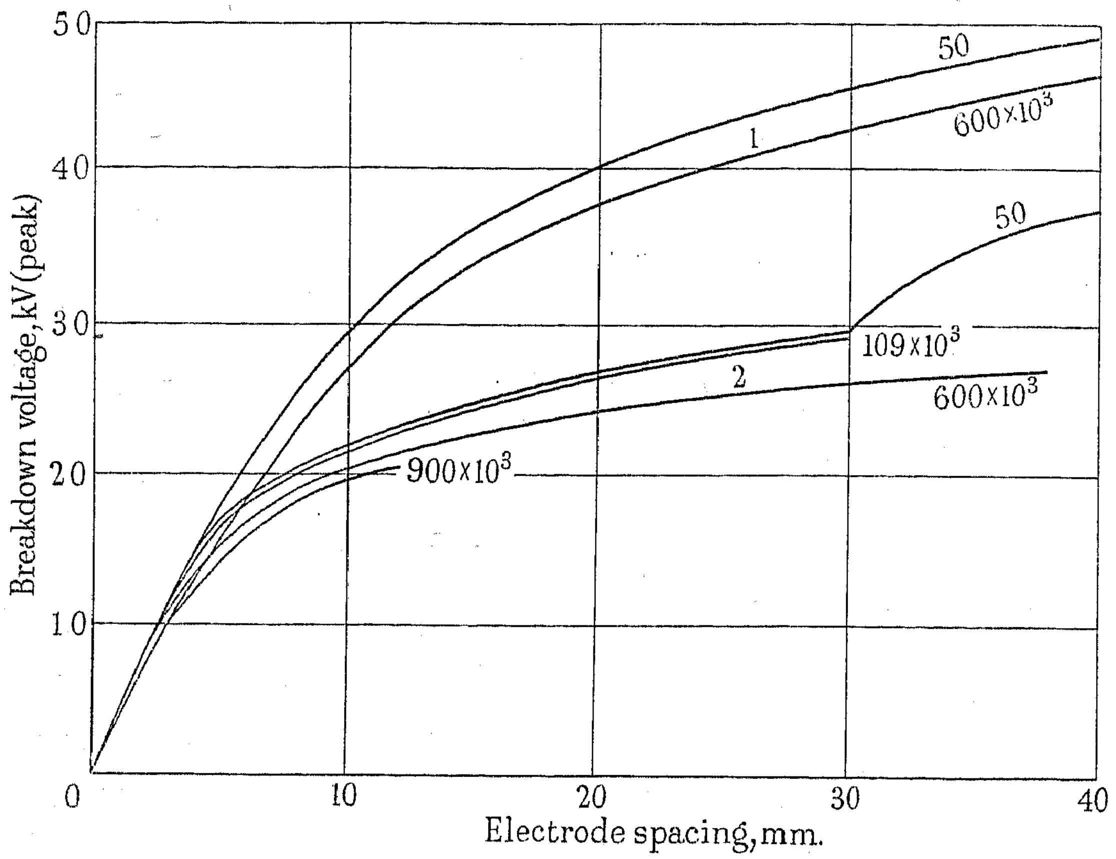

Fig. 3.—Spherical electrodes.

Curves 1. Sphere diameter 14 mm.
Curves 2. Sphere diameter 5 mm.
Figures on curves denote frequency in cycles per sec.

increasing the voltage stress in the intervening air layers between A and C. At some point on the negative half-cycle this stress attains such a value that a discharge passes between the unearthed electrode and the positive space-charge, thus applying the full test voltage to the unbroken air layers between C and B, and complete breakdown follows, unless the electrode spacing is too large.

When the ratio of spacing to diameter exceeds a certain value, depending on the curvature of the test electrodes, a stable brush discharge takes place from the unearthed electrode, and a new set of conditions governs the breakdown of the gap. The brush discharge, as shown in Fig. 5(*b*), is equivalent to an increase in the effective diameter of the unearthed sphere, and complete breakdown follows, according to the above theory, after the brush discharge has been formed. At this spacing, the breakdown is taking place between the earthed electrode and a surface whose radius of curvature has in effect been increased by brush discharge. Thus, at the electrode spacing where brush discharge begins, the curve of breakdown voltage, plotted against length of air-gap, should show a discontinuity of gradient, the gradient changing to a much higher value immediately this spacing is reached. It will be seen from Fig. 3 that the breakdown-spacing curve for 5-mm. diameter spheres, at a frequency of 50 cycles per sec., shows a discontinuity of gradient when the ratio of spacing to sphere diameter exceeds 6. At this and higher spacings a stable brush discharge occurs from the surface of the unearthed electrode.

Brush discharge occurs in nearly all cases only from the unearthed electrode. Electrostatic lines of force emanate from the surface of the unearthed electrode, but a certain number of these lines pass to points at earth potential other than the earthed electrode. Hence a higher potential-gradient exists between the unearthed electrode and the positive space-charge than between the latter and the earthed electrode, and in consequence brush discharge tends to occur, first from the unearthed electrode, followed by complete breakdown. With needle-point gaps, experiments show that brush discharge first occurs from the unearthed point, followed by a less severe brush discharge from the earthed point as the applied voltage is increased. The formation of a stable brush discharge from the earthed electrode in the latter case is due to the exceptionally high potential-gradient existing in the immediate neighbourhood of the earthed point.

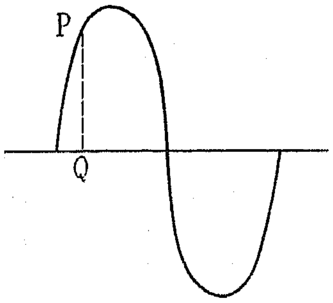

Fig. 4

Experiments with spheres indicate that the voltage gradient between the positive space-charge and the earthed electrode is insufficient to cause brushing, except in those cases where the applied voltage is greater than the critical breakdown voltage of the gap.

It is now necessary to consider the initial ionization conditions when the applied voltage on the electrode gap is less than the critical voltage necessary for breakdown. At the end of one complete voltage-cycle, during which the unearthed electrode is first positive and then negative, the conditions are similar to those described previously, except that the stress in the intervening space between the unearthed electrode and the positive space-charge has not attained a value high enough to cause breakdown. When stable conditions are attained, the positive ions formed during successive half-cycles will be just sufficient to replace those lost due to repulsion. Consequently the positive space-charge will not be augmented during successive cycles, and breakdown will not occur.

EFFECT OF FREQUENCY ON BREAKDOWN VOLTAGE

With a given applied voltage the number of ions formed during a given time will be approximately independent of the frequency, since the formation of ions takes place during the time when the voltage stress exceeds a certain value (PQ in Fig. 4). At all frequencies the numbers of ions produced in a second, for example, will be approximately the same, since the proportion of time during which ion formation occurs is the same at all frequencies.

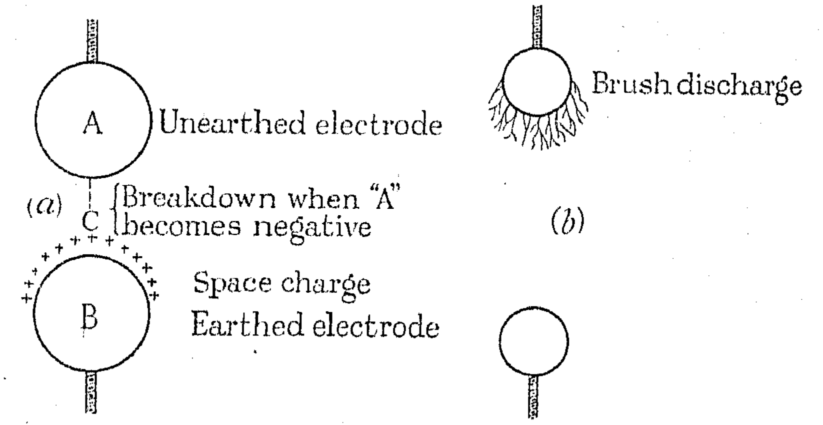

Fig. 5

At high frequencies the ions will be formed in a larger number of short ionizing periods, while at lower frequencies ions will be formed during a smaller number of longer ionizing periods. The number of positive ions lost, however, by electrode repulsion and mutual repulsion will be greater at the lower frequencies, since the "escape" of ions by electric repulsion and mutual repulsion takes an appreciable time before it becomes effective in reducing their number, and there is more time between succeeding cycles at the lower frequencies for the ions to escape or become neutralized before the voltage is applied during the next cycle, and the ionization process continued. The positive space-charge, therefore, is greater at higher than at lower frequency; or, conversely, the voltage at which the number of ions formed is equal to the number of ions escaping is reduced, and therefore the breakdown voltage of the gap is also reduced.

The reduction in electric strength will be proportional to some function of the frequency, and it appears from the preceding discussion that it should be approximately proportional to the frequency. The reduction will be independent of the electrode curvature until a stable brush discharge occurs, when a new set of conditions determines the breakdown of the gap.

These conclusions are borne out by the experimental results. The reduction in breakdown voltage for 5-mm. and 14-mm. diameter spheres is independent of the electrode curvature and is approximately proportional to the frequency, within the limits of experimental error. This is shown by the figures given in the Table.

The reduction in breakdown voltage should increase progressively until the frequency is such that the electrons are no longer able to travel from one electrode to the other before voltage reversal occurs.

Table

VARIATION OF BREAKDOWN VOLTAGE OF SPHERE-GAPS WITH FREQUENCY

Frequency (kc./sec.)	5-mm. diam. spheres		14-mm. diam. spheres	
	Electrode spacing (diameters)	Percentage reduction, calculated on 50-cycle results	Electrode spacing (diameters)	Percentage reduction, calculated on 50-cycle results
109	1	1·5		
	2	1·2		
	3	1·6		
	4	1·4		
	5	1·37		
	6	2·0		
600	1	6·8	1	6·8
	2	6·4	2	6·8
	3	6·5	3	6·8
	4	7·6		
	5	9·2		
	6	10·9		
900	1	11·1		
	2	10·4		

SPARK LAG

It has been noticed that with gaps across which the critical voltage has been applied there is occasionally a lag between the instant of the application of the voltage and breakdown. The "spark lag" may vary from a fraction of a second to a few minutes, and can be explained as follows: When the spark lag is of the order of a fraction of a second a certain number of voltage cycles must be completed at the critical voltage before the space charge is sufficient to start the breakdown. Spark lags of the order of minutes may be explained on the assumption that the applied voltage is slightly less than the critical voltage, and that the space charge is slowly augmented by ionization, such ionization taking place below the normal ionization energy-levels. A normal atom may collide with an ion having less energy than that needed to produce ionization, but with sufficient energy to remove an electron from an inner orbit to an outer one. While the atom is still in this state another collision may take place, resulting in the ejection of the electron from the already excited atom. If a number of such collisions occur, the equilibrium between the positive ions formed and the positive ions escaping during successive cycles will be destroyed and the space charge will gradually increase. The spark lag under these conditions may amount to several minutes.

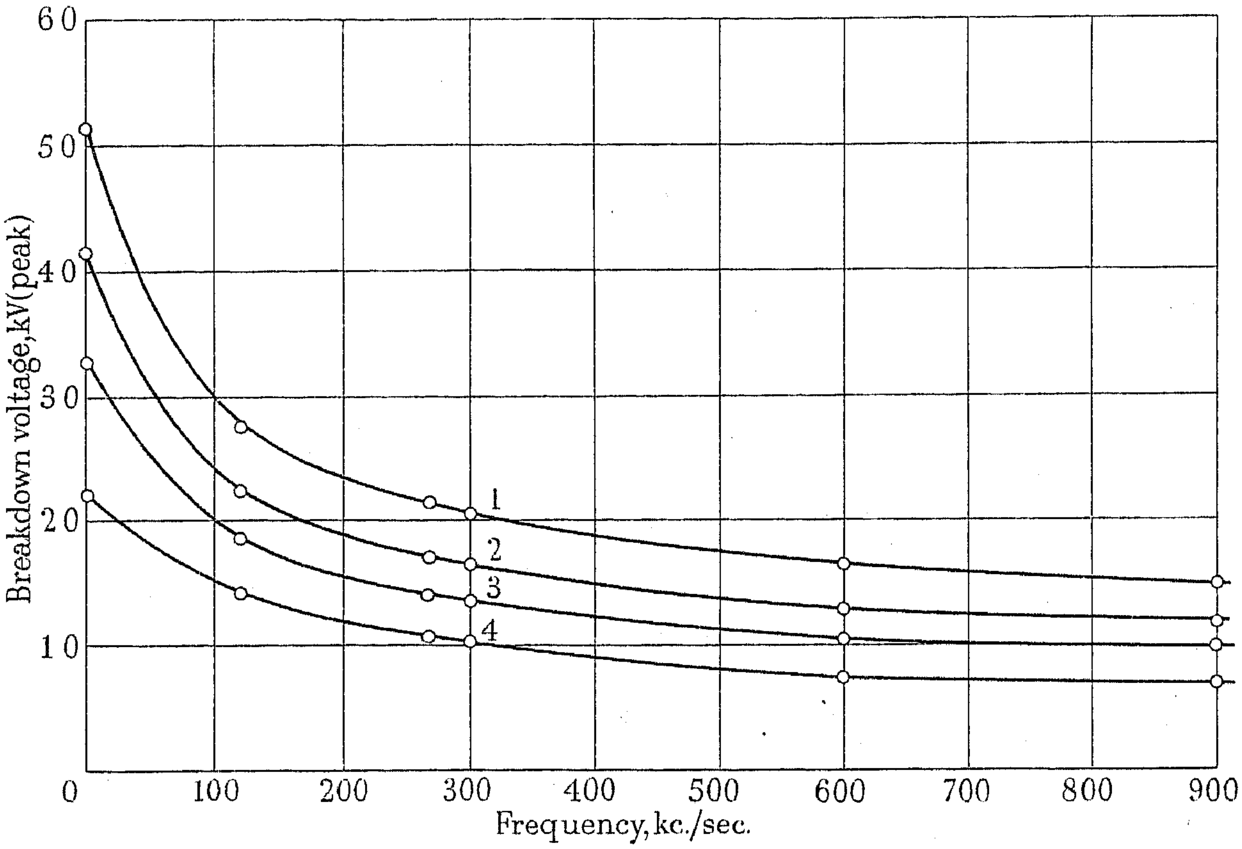

Fig. 6.—Needle-point electrodes.

Electrode Spacing
1. 60 mm.
2. 40 mm.
3. 30 mm.
4. 20 mm.

The increased electric strength of sphere-gaps under impulse-voltage conditions is also explained by this theory. If a single voltage-impulse is applied there is no time-interval in which to build up the space charge, and consequently the voltage necessary to effect breakdown is increased.

NEEDLE-POINT ELECTRODES

Tests with needle-point electrodes have been carried out over a frequency range from 50 cycles per sec. to 900 kc./sec., and the results are plotted in Fig. 6.

With needle gaps, brushing invariably precedes breakdown and a different set of conditions determine the rupture of the gap. Again, as the supply frequency is increased, fewer positive ions escape and the intensity of brushing increases. This places an increased stress on the unbroken air layers, and the breakdown voltage is progressively reduced, until the frequency is such that practically no positive ions are lost by electrode repulsion and mutual repulsion between succeeding voltage-cycles. From the curves in Fig. 6 it will be seen that the strength of the needle-gap is approaching this constant value at a frequency of 600 kc./sec., the change in breakdown voltage between 600 kc./sec. and 900 kc./sec. being very small.

ACKNOWLEDGMENTS

The work described in this paper has been carried out in the Laboratories of Applied Electricity at Liverpool University, and the author wishes to express his indebtedness to Prof. E. W. Marchant for the interest he has taken in the investigation and for his assistance in preparing the manuscript, also to the Department of Scientific and Industrial Research for a grant, and to the University of Liverpool for the Munitions Fellowship which has made this work possible.

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(5) A. Russell: *Journal I.E.E.*, 1919, vol. 57 (Supplement), p. 223.
(6) J. E. Richardson: *Journal of Scientific Instruments*, 1934, vol. 11, p. 82.
(7) E. W. Seward: "Breakdown Strength of Air," *Electrician*, 1936, vol. 117, p. 783.

DISCUSSION ON
"THE DISTRIBUTION OF ULTRA-HIGH-FREQUENCY CURRENTS IN LONG TRANSMITTING AND RECEIVING ANTENNAE"*

Dr. Denis Taylor (*communicated*): Some years ago, whilst carrying out an investigation on the current distribution in loop aerials, I became interested in the ideas put forward by Korshenewsky of the current distribution in open-wire aerials. As Korshenewsky's ideas explained some of my own results with a loop aerial, I carried out a number of confirmatory experiments, but interest in other things prevented me from making a complete investigation. I am therefore glad to see that the authors have pursued the subject further and obtained such good agreement between theory and experiment. My own results, such as they are, confirm their work, but as my experimental technique was somewhat different a short account of it may be of interest.

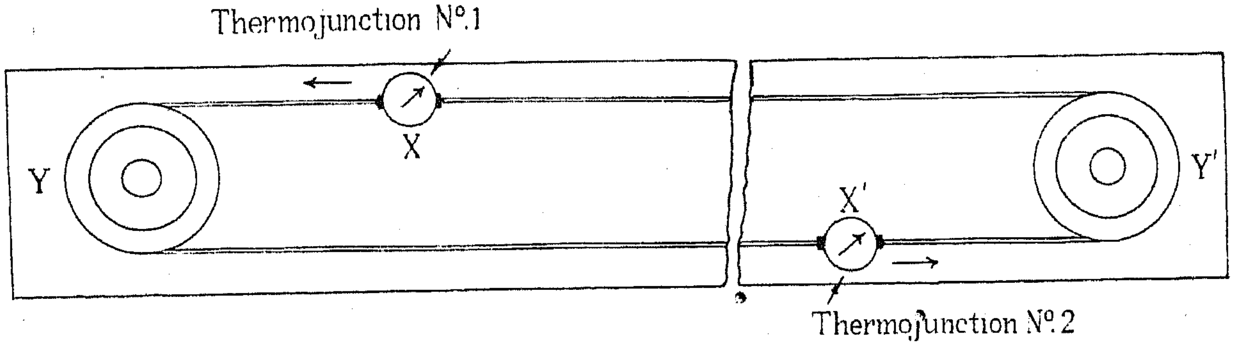

Fig. A

Experiments were carried out at wavelengths from 3 to 5 m. Two D.A.60 Osram valves were used in push-pull in a modified Hartley circuit,† and to this was coupled a dipole aerial of adjustable length. With this apparatus, sufficient power was obtained for adequate radiation over a distance of about 10 wavelengths. The dipole aerial was used horizontally so as to obtain a horizontally polarized wave.

The receiving aerial was of the type shown in Fig. A. Y and Y′ are two small pulleys, and round these is stretched a loop of flexible copper wire. Inserted in this loop are two vacuum thermojunctions X and X′, the points of connection being so chosen that the junctions are always symmetrically placed with respect to Y and Y′. This aerial system was erected parallel to the transmitting dipole, readings of X and X′ were observed as the pulleys were gradually rotated, and a continuous observation of the current and its variation along the length of the antenna was thus made possible. Some care had to be taken in choosing two thermojunctions with exactly the same characteristics, but provided this was done X and X′ showed almost exactly the same variation of current.

So as to avoid long trailing leads the measuring instruments were carried in small baskets, which moved directly underneath the thermojunctions X and X′. Observations were made using a telescope and a periscopic mirror arrangement, and thus errors due to the presence of a moving observer were avoided.

Fig. B shows the current distribution obtained in an experiment carried out with a wavelength of 3·6 m., the length of the aerial being 5·2 m.

I believe this method possesses certain advantages over that used by the authors, in that (i) the whole experiment can be carried out without the receiving aerial being interfered with; (ii) a continuous observation of the current is possible; and (iii) the system is always symmetrical about the midpoint of the antenna. I shall be interested to learn the authors' views on this subject, as perhaps the method possesses disadvantages which their more complete investigation has brought to light.

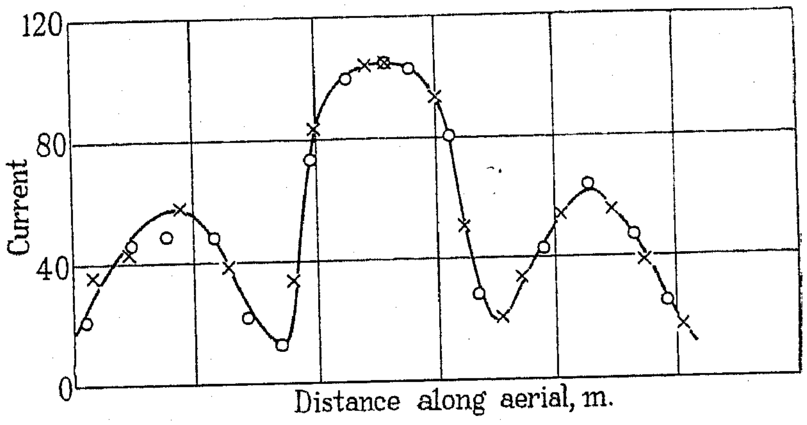

Fig. B

l = 5·2 m. ⊙ Experimental points with instrument X.
λ = 3·6 m. × Experimental points with instrument X′.

The method of moving the thermojunction from point to point in the antenna by unscrewing a portion from one end and screwing it on to the other seems to be quite satisfactory, but I should like to ask whether the authors consider their second method of bridging the antenna with a movable thermojunction to be equally satisfactory. This method was, I believe, first used by Walmsley* in measuring the current distribution in transmission lines, but in applying the method to a receiving aerial where the current is necessarily low I have always found difficulty with the contacts and the variation of contact resistance.

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* Paper by Prof. L. S. Palmer and Mr. K. G. Gillard (see vol. 83, p. 415).

† *Proceedings of the Physical Society*, 1934, vol. 46, p. 76, and 1936, vol. 48, p. 111.

Finally, I should like to inquire whether the authors have found it necessary to use a special type of vacuum thermojunction in their receiving aerial or to modify the experimental procedure with wavelengths of the order of 60 cm. Reduction of the wavelength certainly reduces the size of the aerial systems, and enables the current distribution in aerials comparable in length with the wavelength to be studied without the apparatus becoming cumbersome, but it would seem that some difficulties must necessarily be introduced in the experimental technique.

Prof. L. S. Palmer and **Mr. K. G. Gillard** (*in reply*): It is pleasing to see Dr. Taylor's current-distribution curve for a ratio of $l/\lambda = 1\cdot44$. The general form of the curve is obviously similar to that shown in Fig. 9(*d*) of our paper, which is for l/λ (corrected) $= 1\cdot53$. Dr. Taylor's graph cannot be compared readily with any theoretical curve because the value of the "equivalent length" (in cm. of aerial wire) of his thermojunction for the particular frequency he used, and the effects of phase-changes near the pulleys, have not, presumably, been determined. These effects may probably be equivalent to a length of aerial wire of the order of perhaps 8 or 10 cm. at the frequency he employed. The corrected value of l/λ for his experiments would then be somewhere in the neighbourhood of $1\cdot47$. The agreement between our results is then even more satisfactory.

The economy in time and the general ease of manipulation associated with Dr. Taylor's apparatus is apparent, and it would appear that the mutual reactions between the two wires do not appreciably affect the current distribution, although there must, we think, be some current-component flowing round the closed loop circuit the effects of which will vary with the dimensions of the loop.

A modification of Dr. Taylor's method is to use spring pulleys which wind up the wire at one end while at the same time more wire is unwound from the other end. This method has, however, the disadvantage that the phase-changes on reflection at the ends of the aerial are not quite constant. The method of bridging a short length of the aerial with a sliding thermojunction is not so satisfactory at ultra-high frequencies, and we have now discarded it.

Very small vacuum thermojunctions, if completely stripped of case and external plug terminals and directly soldered into the aerial wire, seem to be quite suitable for ultra-high-frequency work, but need calibrating for each wavelength because their "equivalent length" varies appreciably.

The difficulties of technique increase very rapidly with frequency and, when absolute current measurements are required, the accuracy of the results may be seriously reduced. Even with low power, it is not safe to carry out experiments within the four walls of an ordinary room, owing to the spurious results which usually arise due to reflections.

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* *Journal I.E.E.*, 1931, vol. 69, p. 311.

DISCUSSION ON
"ROTATIONAL HYSTERESIS LOSS IN ELECTRICAL SHEET STEELS"*

Mr. P. R. Bray (*communicated*): I have read the paper with much interest, especially in view of the fact that in January, 1935, I submitted a thesis to London University on the subject, the work having been carried out under the direction of Prof. J. T. MacGregor-Morris. As the author is probably unaware of this thesis I should like to say that the energy-loss curves which I obtained had the sharp peak he mentions, and that the relation between this peak and the "knee" of the *B–H* curve was noted. The general explanation given in my thesis agrees with that put forward by the author, but my own account was not so detailed.

In one particular case the eddy-current loss was allowed for, as the bulk of the measurements were made at 50 cycles per sec. This correction was effected by subtracting from the total energy-loss the energy value given by $\frac{1}{2} BH \sin \alpha_1$, where α_1 is the angle between the *B* and *H* vectors. The error involved in using this expression for the hysteresis loss (instead of $2\pi HJ \sin \alpha$) is negligible for small values of *H*. The correction was applied only for values of *H* and *B* which were known to be pure rotating vectors, of constant magnitude. For higher values of *B* it was assumed that the curve obtained by taking the difference of the two losses increased with *B* in a parabolic manner (eddy-current loss).

Table

B (gauss)	4 000	7 000	12 000	13 500	14 850	16 000	17 500
Hysteresis loss (ergs per cm^3 per cycle) . .	500	1 050	2 250	3 250	4 680	3 700	2 500

Unfortunately, the highest field strength available was about 200 gauss, and it would not have been possible to investigate the decrease of loss at saturation as the author has done, even if the eddy-current correction had been sufficiently precise. The present paper gives some very useful information on this point, as opinion up to the present has been more or less equally divided on the question of the manner in which the loss curve meets the axis of *B–H*.

While the author gets over the difficulty of eddy-current loss, he introduces the complications due to the "grain" of the material, which do not seriously affect a torque measurement at 50 cycles per sec. Furthermore, if the results were to be applied to practical cases, it would have to be assumed that the hysteresis loss per cm^3 per cycle is independent of the speed of rotation of the field. By making some measurements at 25 cycles per sec. it was concluded that this was not true, although Gans and Loyarte were of the opinion that the angle α was independent of the speed of rotation.

Nevertheless, results I obtained on a disc 6 in. diameter and 9·5 mils thick agree fairly well with the author's results. The metal had the following analysis: C 0·07 %, Si 3·8 %, S 0·02 %, P 0·02 %, Mn 0·15 %. This corresponds in the main to the author's Sample 3. The outline of the curve of hysteresis loss plotted against *B* is given by the data in the Table. This gives a curve more peaked than that for Sample 3.

The shape of the curve before the peak is reached depends on the way in which *B* is measured. It was found that there was a sharp rise in *B* as *H* was increased in the neighbourhood of 0·7 gauss, for a rotating field, and that up to the knee of the *B–H* curve the permeability in a rotating field was greater than that in an alternating one, for a given value of *H*. The ratio of the permeabilities had a maximum value of about 1·8.

Both from the theoretical and from the practical point of view it is an advantage to use a method in which the effect of an alternating field can be observed without disturbing the specimen. Results obtained with such a method indicated that the point of inflection of the alternating hysteresis-loss curve occurred at the same value of *B* as the peak of the rotating hysteresis loss, suggesting that one is a form of integral of the other. The general shape of the curves also suggests that the theory might have a statistical basis.

In conclusion, I should like to know whether the author noticed any instability in the value of the loss in the region of the peak.

Mr. F. Brailsford (*in reply*): In making use of the term "knee" when referring to the magnetization curve, I have throughout had in mind that fairly-sharp discontinuity to be observed in the magnetization curve of a magnetically soft material, when the scale of *H* covers a sufficient range to enable the whole of the curve up to near saturation to be plotted. It is the point, for example, at which the curves (*b*) and (*c*) in Fig. 1 turn suddenly away from the ordinate axis. At this point, it is generally agreed, the actual mechanism of the magnetization process changes. Mr. Bray has observed some connection between the magnetization curve and the peak of the loss curve. This is not the consideration brought out by my observations. The particular feature of these is that near the flux density corresponding to the knee of the magnetization curve there is a sharp change in the law relating the rotational hysteresis loss and the flux density, the loss at this point starting to increase, at first, at a more rapid rate. The connection between the discontinuities on the two curves is clearly indicated by the dotted lines in Figs. 11 to 14. The position of the peak of the loss curve is not observed to be related to the shape of the magnetization curve in any particular way.

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* Paper by Mr. F. Brailsford (see vol. 83, p. 566).

With regard to the choice of method for measuring rotational hysteresis loss, it was known from the experience of other investigators and from my own that methods involving the continuous rotation of the field or of the specimen were fraught with considerable difficulties and sources of error, particularly if the specimens were of sheet materials of the usual commercial thicknesses. The method given in the paper was devised and used because of its simplicity and directness. The difficulty of magnetic anisotropy, the "grain" effect, was overcome very successfully by the expedient of the three-disc sample as described in the paper.

The method is admittedly a "static" one and takes no account of any variation of hysteresis loss per cycle which might occur in relation to the speed of the rotation. It is similar in this respect to the determination of alternating hysteresis loss from the area of a hysteresis loop traced out by the usual ballistic method. What the error would be if the static results were utilized to estimate the rotational loss at a rotational speed corresponding to, say, 50 cycles per sec. it is not possible to say for certain. Probably the error, for these commercial materials, would be less than the variation of loss in different samples of, nominally, the same material, or less than the possible errors due to eddy-current corrections, if the rotational hysteresis loss were deduced from measurements with an applied field rotating at that speed. Experimental evidence has been put forward,* in the alternating case, to show that, for a 4 % silicon steel, the "static" loss and the 50-cycle hysteresis loss per cycle are the same within the limits of experimental error. Rotational hysteresis loss might be expected to behave similarly in this respect.

No attempt was made to measure the permeability of the materials in the region below the knee of the magnetization curve, on account of the practical impossibility of obtaining accurate measurements in this region on small discs. I can therefore give no confirmation of the peculiarities referred to by Mr. Bray. I cannot agree that the shape of the loss curves depends on the way in which B is measured, provided only that B is measured correctly and without disturbing the normal flux distribution in the specimen.

The observed spots are seen, in Figs. 11 and 12, to deviate from a smooth curve rather more in the region of the peak than elsewhere. Apart from this there was no definite evidence of any instability of the material in this region.

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* E. A. Neumann: *Zeitschrift für Physik*, 1933, vol. 83, p. 619.

INSTITUTION NOTES

DISCUSSIONS AT MEETINGS

The Council desire to remind the members that contributions to the discussions at meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a " discussion," and that contributions in manuscript should, more appropriately, be sent to the Secretary for publication in the *Journal* as " communicated remarks."

JOINT MEETING OF KINDRED SOCIETIES, 10th MARCH, 1939

The Council have accepted an invitation from The Institution of Automobile Engineers for the I.E.E. to participate in a Joint Meeting of Kindred Societies to be held on Friday, 10th March, 1939, when a discussion will take place on " Factors Contributing to Comfort in Travel." The subject will be dealt with from three aspects as follows:—

(*a*) " Road Travel " by Mr. Sidney E. Garcke.

(*b*) " Rail Travel " by the Rt. Hon. Lord Stamp, G.C.B., G.B.E.

(*c*) " Air Travel " by Captain E. W. Percival.

The meeting will be held in the Great Hall of The Institution of Civil Engineers, Great George Street, Westminster, S.W.1, at 7 p.m. (Light refreshments, 6.15 p.m. to 6.45 p.m.).

A limited supply of advance copies of the paper will be available and can be obtained free of charge before the date of the meeting, on application to the Secretary, I.E.E. Copies of the paper will also be available at the Hall on the night, but only on payment of 1s. 6d. per copy.

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of The Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING

The following are the results of the examinations in connection with the above for the year 1938:—

England and Wales

	Pass	*Fail*
Ordinary Certificates	917	797
Ordinary Certificates endorsed	—	1
Higher Certificates	379	262
Higher Certificates endorsed . .	85	29
Ordinary Diplomas	33	22
Higher Diplomas	9	9
	1 423	1 120

Scotland

Ordinary Certificates	35	22
Higher Certificates	15	2
Higher Certificates endorsed . .	3	1
Higher Diplomas	8	1
	61	26

GRADUATESHIP EXAMINATION RESULTS: NOVEMBER, 1938

Passed*

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Allan, Alexander Frederick Gordon.
Bakhru, Hasso Jethanand.
Birks, Kenneth William.
Bivand, Eric Ernest.
Boden, George Harry.
Cole, Gordon Leslie.
Dean, James.
Gibson, Clarance.
Gilmour, Alexander.
Houston, David.
Hurlston, Frank Arnold.
James, Harry Langford.
Jameson, John Francis.
Jeffery, Edred.
Kubale, John Charles.
McKenzie, Edgar Donald Murdoch.
Maclaren, David Muir.
Menon, Bhakti Vilas Damodara.
Parry, Arnold Holmes.
Pearce, Albert John.
Reekie, Gavin Ralston.
Ritchie, Richard Thomson.
Robertson, James Young.
Scott, Dan.
Sims, Eric Arthur.
Stevens, Stanley Walter.
Storm, Alfred Geberhard.
Sykes, Jack.
Tandy, Thomas Henry.
Turner, Leslie William.
White, Harry William Norman.

Passed Part I only

Alexandre, Arthur Charles.
Baird, Trevor Gordon.
Bentley, Donovan Vernon Craigie.
Fergusson, Leonard.
Foicik, Reginald John.
Hart, Henry Edward William.
Kinsell, David Garrick.
Parker, Walter Brian.
Sneath, Wilfrid Samuel Garwood.
Stickney, Sidney William.
Windows, Clifford Edgar.

Passed Part II only

Donovan, Timothy Denis.
Eales, Edward Reginald.
Greeff, Gabriel Jan Smuts.
Hartill, Philip.
Maddocks, James.
Patchett, George Henry.
Plumbly, Geoffrey Morgan.
Townsend, Ralph.

Further results, relating to candidates who sat for the Examination abroad, will be published later.

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 19th January, 1939, the following elections and transfers were effected:—

Elections

Associate Members

Baldwin, Norman Victor.
Barnes, Reginald Wilfred.
Beckius, Ivar Axel H.
Bourne, Raymond George A., B.Sc.
Browne, Anthony Howe, Lieut. Commander, R.N.
Burt, David Ogilvie, B.Sc.(Eng.).
Callomon, Hans, Dipl.Ing.
Chien, Hung-Van, B.Sc. (Eng.).
Clark, Ronald Isaac H.
Clarke, Hubert.
Cox, Herbert Ernest, B.Sc.
Dodds, John Mathieson, M.A.,B.Sc.(Eng.),D.Eng.
Ford, Lewis Hamilton, M.Sc.(Eng.).
Gunston, John Augustine.
Harlow, William George.
Harriss, George Sydney, B.Sc.
Hawkins, Raymond Cecil.
Heaume, Harry Le Page.
Hogg, Thomas Darling H., B.Sc.
Johnson, Hubert Arthur.
Katz, Lipman, B.A., B.Sc. (Eng.).
McDougald, Frederic Marmaduke.
Masterman, Richard Herbert.
Milne, Edward Ranald A.
Morris, Samuel Arthur.
Neligan, Sean.
Nemec, Ladislar, Ing.
Nicholson, William Thomas A.
Pollitt, Harry Lawrence.
Rayner, Thomas Robert.
Renton, Robert Norman.
Robinson, Oswald Dennis.
Rosenthal, Ernst, Dr.Ing.
Ryan, Edward Raphael, B.E., B.Sc.
Sandilands, Charles Edward.
Schaanning, Alf.
Stretton, Albert Thomas.
Sutton, Frederick Walter.
Villiers, William Amherst, B.Sc.
Walsh, Leslie Haworth, B.Sc.(Eng.).
Webb, John.
Whitehouse, Stanley Francis S., B.Sc., B.Eng.
Wyatt, Charles Burnet.

Companion

Bellamy, Dennis.

Associates

Aish, Norman.
Attard, John.
Barker, Ernest Thomas.
Bradley, Christopher.
Briggs, William Grierson.
Brotchie, Henry.
Brown, Bruce Farrow.
Brown, Kenneth Ivon.
Bryan, Francis Charlton.
Buley, Frederick Arthur.
Cartlidge, Robert.
Chaudhuri, Chandra Kisore.
Dutt, Jagat Bandhu.
Gamlen, Robert Eric.
Goymer, Robert Tilt.
Grocott, Gilbert Henry.
Hall, Robert James.
Hollingsworth, Douglas Taft.
Hulme, Harold Ian.
Jarvis, William Frederick.
Jones, John William.
Kant, Thomas Young.
Kington, Arthur Charles.
Kirkwood, William Scott.

Associates—continued.

Knight, Harold James.
Lowe, Harold.
Mankin, John Marsden.
Mann, Jesse.
Pearce, Frank Haliday.
Pearson, Laurence Herbert.
Robertson, Norman Charles.
Robinson, Raymond.
Scriven, Ernest.
Smith, John Dudley.
Smith, Norman Anderson.
Tattley, John.
Tunnadine, Francis Wilfred.
Wedge, George Arthur.
Wesker, Henry Thomas.

Graduates

Aiya, Santebachahally Vishakantaiya C.
Allan, James Douglas.
Allison, Kenneth Walpole.
Ananin, Leo, B.Sc.(Eng.).
Baker, Cyril Clarence T., B.Sc.
Beck, Geoffrey Edward, B.Sc.
Berrill, Leslie Howard.
Black, Peter, B.Sc.
Böhm, Kathe, (Miss).
Bonson, Harold Godfrey, B.A.
Bosworth, George Simms, B.A.
Boundy, James Reilly, B.Sc.
Brocken, Patrick Thomas, B.A., B.Sc.Tech.
Byrne, Denis Joseph.
Cameron, Kenneth Allerton, B.Sc.(Eng.).
Cannell, John Anthony, B.Sc.
Carey, Logan Boyce, M.Sc.
Ceballos, Francisco Rodriguez, B.Sc., M.E.
Chambers, William Roughley.
Chang, Chi-Yin, B.Sc.
Chaplin, Frank Frederick.
Chapman, William Glanville, B.E.
Cherry, Edward Colin, B.Sc.(Eng.).
Chien, Ying-Kwan, B.Sc. (Eng.).
Chiu, Foo Sung, B.Sc.
Collier, George Elder.
Conradi, Gordon Henry E.
Cronshaw, Frederick William.
Crossley, John, B.Sc.
Darby, John Stanley.
Das-Gupta, Bikash Chandra, B.Sc.
Davies, Henry.
Dew, Boon Seng, B.Sc. (Eng.).
Dolay, Necati Ahmet, B.Sc.
Dowie, Thomas.
Edwards, Thomas.
Foss, George Henry, Flight Lieut., R.A.F., B.Sc.
Francis, Alfred John.
Furlow, Aubrey.
Gehrmann, August Shaw, B.E.
Glyde, Thomas Charles W.
Goering, Peter Hermann.
Gosling, James Charles.
Grimes, Wilfred Wallace.
Hanna, William John, B.Sc.
Harding, George Roland, B.A.
Hewett, Martin Hollingsworth.
Hick, George.
Hull, John Neville, B.Sc. (Eng.).
Hunt, John Headley, B.Sc. (Eng.).
Jack, David Mervyn, B.Sc. (Eng.).
Jaggia, Shanti Sarup.
Jinks, Charles Edward.
Jones, James Trevor, B.Sc.
Lamond, John Alan, B.Sc. (Eng.).
Lawrence, Solomon, B.Sc. (Eng.).
Leeper, Frederick.
Le Manquais, Frederick Charles, B.Sc.
Ma, George Char-Kee, B.Sc.(Eng.).
MacCrimmon, William Monro.
McGinn, Ronald.
Malcolm, Lewis John.
Malik, Fateh Ali, B.Sc. Tech.
Malkani, Gurbuxsing Ramchand, B.Sc.Tech.
Manley, George William.
Mason, Arthur John.
Merz, Robert De Satur, B.A.
Miller, Charles Herbert.
Morphet, William Henry.

Graduates—continued.

Muirhead, David Pearson.
Murthy, Dodballapur Krishna, B.E.
Nadel, Joseph, Dipl.Ing.
Newman, Eric William.
Osborn, Jack Herbert, B.Sc.
Outhwaite, Edward.
Parker, Maurice John, B.Sc.(Eng.).
Pendlebury, Francis Douglas, B.Sc.
Peters, John Henry C., B.Sc.(Eng.).
Pile, John Hinton S.
Pilkington, Basil Kenneth.
Posnansky, Raul, Dipl.Ing.
Prasadarao, Rettiganti Venkata D., B.Sc.
Reynolds, Douglas, B.Sc.
Ricketts, Charles William, B.Sc.
Roberts, Andrew D'Arcy, B.Sc., B.E.
Robson, Alexander, B.Sc. (Eng.).
Roy, Robert James.
Schumann, Hans Egon.
Selig, Karl Ludwig.
Shaw, Robert Phillips.
Shepherd, Frederick Leonard.
Sia, Ven, B.Sc.Tech.
Slater, Joseph Russell, B.Sc.
Strang, William Braithwaite, B.A.
Sutton, Alick Graham, M.A.
Tasker, George Frederick.
Taylor, Herbert Stanley, B.Sc.(Eng.).
Thorne, Kenneth Gilbert.
Tower, Arthur Owen.
Too, Joon Ting, B.Sc.
Tyler, Victor Joseph, B.Sc.
Tyson, Benjamin F., M.Sc.
Vanstone, Frederick Haydn, B.Sc.
Vincent, Paul Michel.
Viswanathan, Viswanathar Kanagaratnam.
Ward, Donald.
Watson, William, B.Sc.
Westcott, Nicholas.
Windett, Eric Percy.
Wong, Yat Sing, B.Sc. (Eng.).
Wood, Stanley George.
Yee, Ting, B.Sc.
Yuen, Sze-Fong, B.Sc. (Eng.).

Students

Abbott, Hugh Hector.
Abercrombie, Stanley Douglas.
Abraham, Norman Alexander.
Adeler, Ralph Stig A.
Agnihotri, Narayan Prasad.
Alger, Alan James.
Allam, Joyce, (Miss).
Allan, James.
Amar, Dwarka Das.
Ambegaonker, Raghunath Damodar.
Amonkar, Vishwanath Rajaram.
Anderson, Charles Neil.
Ansley, Ronald Edward.
AppukuttanNayar, Parameswaran Pilla.
Archer, Douglas.
Arcus, Geoffrey William, B.Sc.(Eng.).
Astridge, John Leslie W.
Atcherley, John Denison, B.A.
Aust, Arthur Thomas.
Austin, John.
Badham, John Henry.
Bailey, Albert Ernest.
Baker, Richard George.
Balasundaram, Coimbatore Anantapadmanabha.
Baldry, Ernest Edward.
Ball, Charles Edward.
Ballard, Peter Fairs.
Bamji, Burjor Kaikobad.
Barber, Alan.
Barclay, Robert Stuart.
Barlow, Gordon Alfred.
Barnes, Frederick Ecton.
Barnett, John Alan.
Barrett, Philip Alan.
Bartley, Lawrence James.
Barton, Bernard.
Bawa, Balbir Singh.
Baxter, Arthur Albert.
Baxter, James.
Bayton, Cecil Charles.
Beach, Jack.
Beattie, Malcolm Hamilton.
Beaumont, Ernest.
Bedi, Shanti Lall.
Bell, Hugh.
Benjamin, Arthur.
Bentall, Anthony Alfred L.
Bergna, Larry.
Berry, Jack Sloane.
Bettinson, Sydney Francis.
Bhakat, Bhabani Prosad.
Bhar, Gopal Chandra.

Students—continued.

Bhatia, Kishan Chand.
Bicket, James Howie.
Bircumshaw, Ross Manly.
Black, Keith Ferguson.
Blagden, Richard.
Boh, Khaw Kai.
Book, John William.
Bowen, Dennis Dawes.
Bradford, John Percival.
Bradshaw, Harold.
Brampton, George Alfred.
Brewer, Astley John S.
Broacha, Jamshed Ardesir.
Brodrick, Alfred Gerald.
Brookes, Maurice Meridyth.
Brown, John Hastie.
Brown, Thomas.
Brown, William Albert E.
Browne, Geoffrey James.
Buchanan, Robert Hamilton S. M.
Bugler, Frank Earnest W.
Burgess, Frank Robert.
Burrow, Robert Guy.
Burton, Wilfred.
Busby, Joel Derek A.
Butler, Charles George.
Buxton, William Joseph.
Campbell, Alexander Matthewson.
Campbell, John McKay.
Campbell, Robert Henry.
Caprihan, Mehar Chand.
Carnegie-Rumboll, John.
Carruthers, Robert.
Chadha, Om Paul.
Chapman, Leslie Charles.
Chatterjee, Jyotirmoy.
Chatur, Parshva Chandra.
Christie, Kenneth.
Clark, Reginald.
Clarke, Esmond Victor.
Clement, Eric William.
Clement, Leslie Frank.
Clotworthy, Neil Desmond.
Coates, George Stanley.
Cockerton, David Edward.
Coker, Antony Lewis.
Cole, Thomas James S.
Colledge, Alfred James.
Collins, Thomas Kenyon G.
Cooper, Richard Anthony, B.Sc.(Eng.).
Corbett, Jack Murray.
Coupe, Arnold.
Coutts, John Edward.
Coventry, John Herbert.
Cox, Arthur William G.
Coxon, Herbert William.
Coysh, Charles Robert M.
Cranston, Eric Frank.
Crocker, Leslie John.
Cullen, Alexander Lamb.
Cuthbert, Cecil Alexander.
Da Costa, Francis Edward.
Daoud, Daoud Antoun.
Darukhanawala, Beheram Jehangirji.
Daruvalla, Dinshaw Maoroji.
Davidson, Alexander Matthew.
Davidson, Cyril Mitchell.
Davies, Brian Talbott.
Day, William Idris.
Dean, Thomas William.
de Lisle, Edwin William.
Deshpande, Prabhakar.
Dhall, Chuni Lall.
Dilley, Arthur Frank.
Dimbleby, Leslie Charles.
Dingwall, Norman Pirie.
Diwanji, Kulinkumar Ranchhodlal.
Dodd, Thomas Frederick.
Donaldson, James.
Dougal, Samuel.
Dowsing, Douglas Robert F.
Draycott, Kenneth Vernon.
Duncan, Walter Andrew M.
Dunnill, Alan.
Dyson, Douglas Annett.
Ede, Alexander James.
Edwards, Jeffrey Rhys.
Ellingham, John Henry G.
Esterson, Maurice.
Evans, Brian Richard.
Evans, Gordon Edward, B.Sc.
Fairman, William George.
Fawcett, Dennis.
Fell, Duncan Macmillan.
Fenemore, Ronald William.
Fennell, John Francis, B.A.
Fernando, Joseph Montagu.
Fitton, Edward Douglas.
Flashman, John Sydney.
Foulds, Henry Charles G.
Foy, Frederick Harold T.
Francis, Edwin John H.
Frankland, George Douglas.
Friend, Frederick John.
Fuller, Frank Martin.
Gammon, Jack.
George, Kunnumpurathu Easaw.
George, William.
Gericke, Michael Roelof.
Ghosh, Phanindra Krishna.
Gilmour, John.
Gladwell, John Spencer.

Students—continued.

Gladwin, Arthur Sullivan.
Goldie, Arthur Kirton.
Gomersall, Fred.
Gopalakrishnan, S.
Gordon, Douglas Stuart.
Govas, George Harold, B.Sc.(Eng.).
Green, Fred Battersby.
Green, Raphael Samuel.
Gregory, Kenneth George.
Gregson, John Archer E.
Griffin, Percy Alexander.
Griffiths, Llewellyn James.
Griffiths, Ronald John.
Grubb, Kenneth Oliver.
Gurr, John Henry.
Gursahani, Dunichand T.
Hague, Philip.
Halfhide, William Ralph.
Hall, Peter Dudley.
Hall, Stanley William.
Hancox, Norman.
Hanley, William Brian.
Harris, Roy Alfred.
Harston, John Michael.
Hart, Edward Chichester.
Hart, Frederick John.
Hart, George Valentine.
Harvey, Dennis Gustav.
Harvey, George Vernon.
Hattangady, Vasant Rao.
Hawkins, Philip Owen.
Hay, William Andrew H.
Hay, William Jean.
Heidemstam, Felix Henry.
Heley, Alexander Walter.
Heppell, Hugh Kenneth.
Higgin, Ronald Lupton.
Hiramanek, Dady Hirjibhai.
Homewood, Norman Kenneth.
Hood, Norman Lovell.
Horner, Eric.
Horowitz, Theodore.
Howard, Richard.
Howard, Ronald.
Howell, Frederick Raymond.
Howes, Norman.
Howles, Donald Arthur.
Howles, Lawrence Reginald.
Hubbard, Robert Walter.
Hulls, Gerald.
Husemeyer, Norman Stanley.
Hutton, Joseph Charles.
Hyde, Melville Leonard.
Inurrieta, Enrique.
Irwin, Hew Charlton.
Jackson, Edward Mellersh.
Jakati, Vasant Hanmant.
Jamieson, William.
Jani, Jayantilal Balkrishna.
Jarrett, Norman Charles.
Jarvis, John Cecil.
Jeffcote, Thomas Bernard.
Jenkinson, Frank Edward.
Job, John Vivian E.
Johnson, Arthur Vernon.
Johnstone, Wilfred Gordon.
Jones, Peter Bailey.
Jones, Raymond Lewis.
Joyce, Edgar Arthur.
Kagalwala, Abedin Fidahusein.
Kale, Mahadev Ganesh.
Kale, Mahadev Ramchandra.
KamaSastry, Yellapantula Venkata.
Kamir, Hari Singh.
Karaosman, Mahmut Naim.
Kashyap, Kundan Lall.
Kepple, Saxon Frank.
Keys, Maurice George.
Killick, William John.
Kingravi, Iftikhar Ahmad.
Kinra, B. R.
Kirkpatrick, Hugh Alexander.
Knight, Fred.
Knowles, William.
Kochhar, Om Parkash.
Koppar, Venkatesh Gopalrao.
Krishna, Brij.
Krishnan, Subrahmanya.
Kumar, Pratap.
Kundu, Dev Narayan.
Ladd, William Jesse.
Laity, Gerald Wilmot.
Lakin, Ralph Thornton.
Lall, Arya Ram.
Lamacraft, William Francis H.
Lang, Raymond Collie.
Langford, Robert.
Langhorne, Thomas Blacklock.
Lear, Desmond Herbert, B.Sc.
Lee, William Clayton.
Lees, Edward James.
Lefeaux, George Sutton.
Leng, Irving James.
Lilley, Frank Harrison.
Lim, Yew Yin.
Lloyd, Arthur George.
Lloyd, Wallace.
Long, George Richard.

Students—continued.

Longman, Peter Henry.
Lord, Will Gibson,
Love, Douglas Ronald.
Lumley, William Gray.
Lynott, Terence Patrick.
Lyons, Ralph.
McFarlane, Charles John.
Mackinnon, Ian Bannatyne.
MaCrae, William.
McWilliam, Albert George.
Makin, Neil Meredith.
Malik, S. L.
Manley, Richard Tapley.
Markley, Jack Hayward.
Marlow, John Henry.
Mascarenhas, Joseph Lawrence P.
Massey, Philip.
Massiah, Cuthbert Aloysius.
Masters, Maurice.
Mathur, Rang Lal.
Maude-Roxby, Bryan Noel I., B.A.
May, Jack Douglas B.
Meadowcroft, John Raymond.
Mehra, Madan Lall.
Mehta, Dewan Singh.
Menon, G. Unnikrishna.
Metcalf, Edward Thomas.
Middleton, Herbert Irwin.
Miles, James Albert.
Millar, James Robertson.
Miller, Donald Halliday.
Millyard, Leslie Winstanley.
Milner, George Wallace.
Mishra, Sharat Chandra.
Mitchell, Geoffrey.
Mitchell, John.
Mitchell, Leonard Matthew.
Mitchell, Maxwell Leonard.
Mitter, Jagdish.
Modak, Yeshwant Bhaskar.
Mohgaonkar, Raghunath Narhar.
Monk, Hugh Winterbotham.
Montague, Gladwyn Robert.
Monteath, George Dewar.
Moore, Stanley John.
Moos, Julius Ernst H.
Mortifee, Douglas William.
Moynham, Frank Edward.
Mudhur, Jaswant Singh.
Mugaseth, Sam Bomanshaw.
Mundal, Arthur Ajit K.
Mussell, Alexander.
Mycock, Percy Victor.
Nadkarni, Prabhakar Shankarrao.
Naik, Dundappa Baba.
Nankivell, John Howard.
NarasimhaReddy, G.
Neal, Thomas Alfred.
Ness, Richard Horrabin.
New, George John.
Newton, Frederick William.
Nisbett, William Abbott.
Nixon, Frederick John.
Noad, Dennis Edward.
Norman, Arthur Ernest.
Norman, William John.
Noronha, Benedict Lactancio.
North, Cyril Arthur.
Oakes, Charles Trevenen.
O'Connor, John Richard W.
Ogden, Ronald Samuel I.
Ogle, Harry Russell.
Ohri, Bikram Das.
Oldroyd, Geoffrey.
Orchard, Leonard George.
Osbourne, James Knox.
Padia, Himmatlal Makanji.
Page, Norman Ben.
Palmer, Harold Ernest.
Pardo, Nehemiah.
Parker, John Reginald.
Parshad, Ram.
Patail, Sulaiman Mohammed.
Patel, Chinubhai Manibhai.
Patel, Jayantilal Amritlal.
Patel, Veerbhanu Gokalbhai.
Pateman, Maurice Charles.
Patil, Parvatgouda S.
Paulden, Robert Stewart.
Peake, Alfred Hugh.
Phaterpekar, Digamber Kashinath.
Pinson, John Lloyd.
Pollard, John Padriac Weippert.
Powell, Arthur Richard.
Prabhakaran Nayar, Chandrasekharan Rajarajavarma.
Prabhakarasarma, Felavarti.
Pramekamol, Pratan.
Price, Robert Cecil.
Price, William James, B.Sc. (Eng.).
Priddis, John Edward.

Students—continued.

Prins, Aurele Gerald E.
Prout, Donald Cornell.
Pyman, Lawrence Lee, B.A.
Pyrah, Thomas Hutchinson.
Quayle, John Pattinson.
Rai, Mukand Lal K.
Rakshit, Bimal Kumar.
Ramadurai, V.
Ramamoorthy, Obla Rajagopllier.
Ramanujachari, Komanduri.
Ramaswamy, Paranji Rangaswamy.
Rammohan, Sundaram.
Ramsbottom, John Craven.
Rao, Mocherla Kutumba.
Rao, S. Venkat.
Reading, Norman George.
Redmond, James.
Rees, Richard Aubrey.
Richards, Francis Arthur.
Richardson, Michael Brodie.
Richmond, Joseph Raymond W.
Roberson, Roland Stanley.
Roberts, Alec Charles.
Robinson, Douglas William.
Robinson, James Alfred.
Roper, John Frank.
Rosenbrock, Howard Harry.
Rushforth, Harold.
Ryan, Cecil Thomas J.
Saggar, Gur Pyara L.
Sanmugaraja, Nadaraja.
Sarkar, Nirendra Nath.
Sarna, Bal Raj.
Savage, John Openshaw.
Saw, Frederick Strickland.
Saxena, Sharda Charan.
Saxon, Godfrey.
Schofield, Michael William.
Scholes, Noel Parnell.
Scott, Alisdhair Hendry E.
Scott, George Graham.
Scott, Maurice Robert H.
Scott, Robert.
Scott, Tasman Huia.
Sen, Rabindra Nath.
Seymour, Trevor.
Shah, Mohd Ashraf.
Shah, Ramanlal Keshavlal.
Shepherd, George Ronald.
Shepherd, John.
Shepherd, John Charles W.
Sherriffs, Douglas Leon.
Shetty, P. Sanjiva.
Shotter, Hugh Anthony.
Silas, Ezekiel Ezekiel.
Singh, Bhanu Pratap.
Singh, Gurcharn.
Singh, Harbakhash.
Singh, Puran.
Sivasankaran, N. K.
Skinner, Ernest John.
Skinner, John Chynoweth.
Slater, Patrick Lawson V.
Smellie, George Horne.
Smith, Charles Walter.
Smith, Douglas William J.
Smith, Frederick Roland C.
Smith, Peter Humphrey.
Smith, Raymond Ernest.
Smithson, William Harold T.
Smuts, Michiel Nicolaas.
Soloman, Aaron.
Soundarararajan, S.
South, John Denton.
Speakman, Raymond Holden.
Speke, Kenneth.
Spencer, Allan.
Stace, Ian Ormonde.
Starnes, Harold William.
Stefanelli, Raffaele Giuseppe F.
Stenning, Bernard Frank.
Steward, Peter Stanley F.
Streat, Philip Edward.
Subbaraman, M.
Subramani Aiyar, Ponkunnom Narayana.
Subramanian, Bhavani Anantharama.
Sugden, Charles.
Suryanarayanan, Nallur Sivarama I.
Sussmann, Milo.
Sutton, Arthur John.
Sutton, George Gurney.
Swanson, John Sydney T.
Sykes, William Harrison.
Symons, James Michael D.
Taberner, James Walter.
Tamboly, Kaiki Sorabji.
Taylor, Geoffrey Stewart.
Taylor, Leslie.
Taylor, Neil McDonald.
Teicher, Ludwik.
Tharia, Adam Jusab.
Thompson, Gresham Thomas.
Thornton, Leslie Bernard.
Thukral, Mushtaq Rai.
Trapnell, Arnold Humphreys.
Trask, Peter Darien.

Students—continued.

Treweek, Kenneth Hewer.
Tricker, Charles Spencer.
Tucker, Ernest.
Tweedie, Maurice Charles K.
Twitchin, Frederick Eric D.
Upadhyay, Ravishanker Manishanker.
Usher, Eric Frederick F.W.
Vajifdar, Maneck Bapuji.
Van Dorp, Simon Dirk.
Varshneya, Mahesh Chandra.
Venkatram, Gopal.
Vexler, Nataniel.
Wakefield, John Anthony.
Walker, Duncomb Wallace.
Walker, Frank.
Walker, Robert Stephen.
Walker, William.
Ward, Norman Charles.
Waters, Gordon Edmund.
Watson, David William.
Watson, Douglas Lewis.
Webb, Norman David.
Weinbaum, Isaac.
Wells, David Woodward.
Whitaker, Arthur John.
White, Frank William H.
White, John Richard.
Whiting, Frederick Brian.
Wiblin, Ellis Roussel.
Wilcox, Arthur.
Wilkins, Geoffrey Ronald.
Wilkinson, Donald Frederic.
Wilkinson, William Herbert.
Wills, Reginald John.
Wilson, Alan John.
Wilson, Graham Rudge.
Wilson, Joseph Thanaraj V.
Winglee, Cecil Ng.
Witt, Frederick Harry.
Wong, Sun-Man.
Wood, Arthur Buckley.
Wood, Reginald John.
Woodham, Stanley Howard.
Woodley, Ernest James.
Worthy, Edward Jack.
Wright, Cecil Scott.
Wright, Rowland.
Yodmani, Sombati.
Youett, John Frederick.
Zaky, Mohamed Taha.

Transfers

Associate Member to Member

Bleach, Chris Charles.
Clinch, William Norman C.
Cluley, Gordon.
Dance, Herbert Ernest, M.Eng.
Eclair-Heath, Stanley.
Grinstead, Leslie.
Grose, Stewart Jewell, B.Sc.
Grundy, Eric, B.Sc.Tech.
Harral, Richard Harold.
Jolly, Edward Ernest.
Jones, Frank, M.Sc.
Jones, John Richard.
Kenny, John Aloysius.
Kidd, William.
Lacey, Harold Morgan, B.Sc.
MacColl, Albert Edward.
Mackay, David Hymers, B.Sc.
Maddock, Gerald Maxfield.
Midgley, Harry, M.Sc.
Miller, James.
Millward, Gerald Richard.
Monk, Sidney Gordon, M.Sc.(Eng.), B.Sc.
Morgan, John.
Murphy, Patrick Gerard, B.E., B.Sc.
Murray, Ian Norman, B.Sc.
Orkney, John Carnegie, B.Sc.
Proud, Harry Melville.
Raworth, Arthur Basil.
Riley, Harold, M.C., B.Sc.
Ripley, Dunstan.
Robinson, Douglas Harry.
Rowse, Arthur Albert, M.A., B.Sc.
Rudra, John Jitendranath, M.A., B.Sc., Ph.D.
Shepherd, George Raymond, B.Sc.(Eng.).
Smith, William Francis, B.Sc.
Swann, Herbert William.
Thompson, Harry Francis J.
Tucker, John Potterton.
Turton, Leonard, M.Eng.
Watson, Alfred, B.Sc.
Wellings, John Gale.
Wells, Brian Lewis, B.Sc.(Eng.).
Wells, Reginald Iredale, B.Sc.(Eng.).
Wilson, James Haynes, M.C.
Wright, Esmond Philip G.

Associate to Associate Member

Adamson, Maurice William.
Ashton, Norman.
Blofeld, Thomas Guest.
Capper, Frank Wilton.
Capper, Sam.
Clark, Walter Charles.
Deacon, Edwin Arthur.
Gardiner, John Henry.
Green, George Norman.
Handley, William Cecil, B.Sc.Tech.
Lowe, Reginald Gretton.
Macdonald, William Ewing.
Shipton, Percy John.
Wilson, Charles Henry.

Graduate to Associate Member

Alexander, William, B.Sc. (Eng.).
Allen, Maurice, B.Eng.
Angus, John Lavis, B.Sc.
Anketell, Cecil Augustus R., B.Sc.(Eng.).
Ashworth, John Edwin N.
Bagnall, Richard Stephen D.
Bailey, Herbert Bolton, B.Sc.
Bailey, James.
Bond, William Alfred, B.Sc.(Eng.).
Brand, Frank.
Brenan, Cecil Fynes C., B.Sc.
Brook, John Lewis.
Buchan, William Morris, B.A.
Campbell, Harry, B.Sc.
Carr, Clifford.
Carter, Geoffrey William, M.A.
Channing, William Kentish.
Cuthbert, Robert.
Dallimore, Joseph George, B.Sc.(Eng.).
Davies, M. Wynn Humphrey, B.Sc.
de Silva, Gostinnawadu Francis.
Dingwall, Ronald.
Drummond, Bernard Gilbert.
Easterbrook, Alan Bickle.
Eatock, James.
Evans, Donald Wentworth.
Ferry, Henry, B.Sc.(Eng.).
Fletcher, Paul Thomas.
Flint, Ernest Alfred.
Garrett, Maurice Arthur.
Hayes, John Barry, B.Sc. (Eng.).
Hempsall, Cyril.
Heppenstall, Frank Evelyn, B.Sc.
Jones, Sydney, B.Sc.
Keen, John Horsley.
Kelly, Richard Gould.
King, James Lionel.
Laine, Howard Bunch, B.Sc.Tech.
Lake, Richard Arthur, B.Sc.
Lautier, Vincent.
Lee, Bernard Crossley, B.Sc.
Leighton, Gordon Loftus, M.Sc.Tech.
Leverton, John Henry, B.Sc.(Eng.).
Lombard, James Stephen, B.Sc.(Eng.).
Mabe, William Stanley, B.Sc.
McCarthy, Edward Henry.
McGuffin, Harry, B.Sc.
Maiden, Frederick Hugh.
Marryat, Robert Anthony, B.Sc.(Eng.).
Mathieson, Edward John.
Mayo, Stanley Jack.
Medcalf, Wilfred Henry, B.Sc.(Eng.).
Melhuish, Alan, B.Sc. (Eng.).
Mody, Rustom Jehangir, B.Eng.
Moir, Alexander, B.Sc.
Moss, John Francis.
Murrell, Alan Percy C.
Nally, Rickard Michael.
Newing, Alan.
Newling, Vernon Henry, B.Sc (Eng.).
Oldcorn, Eric Carlton T., B.Sc.
Olson, Andrew Hugh F., B.Sc.(Eng.).
Oswald, Thomas Dobson, B.Sc.
Panter, Charles Hugh.
Peirson, Garnet Frank.
Phillips, James Huntley, B.Sc.
Pickles, Thomas.
Railton, Edgar Charles, B.Sc.(Eng.).
Rankin, George David.
Rawcliffe, Gordon Hindle, B.A.
Rickett, Donald Harry, B.Sc.(Eng.).
Ridding, Arthur.

Graduate to Associate Member—continued.

Rowbottom, John Radcliffe.
Schroter, Edward.
Seddon, Fred.
Sharples, John, B.Sc.(Eng.).
Singh, Kehar.
Smith, Dick, B.Sc.(Eng.).
Smith, Maurice Joy, B.Sc. (Eng.).
Smith, Theodore Strongetharm, B.Sc.(Eng.).
Stoyle, William Arthur R., B.Sc.
Sykes, Clifford, B.Sc.
Taylor, Harold Frederick R.
Thistleton, Richard.
Throsby, Frank Stanley.
Tigwell, John Selby.
Uden, Frank Arthur.
Vickers, Jack Stanley, B.Sc.(Eng.).
Wagstaff, John Harwood, B.Sc.(Eng.).
Wallace, Samuel Archibald, B.Sc.
Webber, Cyril Benjamin.
Webber, Frederick William J., B.Sc.(Eng.).
Weller, Herbert Lewis.
Wey, Raymond John.
Wickremesinghe, Mervin Lionel, M.A.
Williams, Emrys.
Willoughby, Eric Osborne, B.A., B.E.E.
Woolgar, Charles Ernest, B.A., B.Sc.
Yardley, Robert Oliver.

Student to Associate Member

Sumner, Stephen Bailes.

Student to Associate

Negus, Edgar Walter D.
Roy, Tara Bilas.
Watling, William George A.

The following transfers were also effected by the Council at their Meeting held on the 5th January, 1939:—

Student to Graduate

Allsop, Arthur Geoffrey.
Baker, Arthur.
Bhagawat, Sadashiv Ramchandra, B.Sc.
Burt, Harry Kyle P., B.Sc.
Butcher, Ernest Thomas.
Candler, John Lawrence, B.Sc.(Eng.).
Catto, Eric Herbert.
Dobbie, Arthur Kenneth, B.Sc.(Eng.).
Drayton, Cyril Robert.
Evans, John Dudley, B.Sc. (Eng.).
Fartash, Nosratollah.
Gildea, Patrick James H.
Goodall, William James.
Hargreaves, Thomas Frederick S., B.Sc.(Eng.).
Hibbs, Edwin Charles.
Hilton, James Whittaker.
Hunter, Alan Orville, Junr., B.Sc.
Iago, John Martindale, B.Sc.(Eng.).
Jones, William Owen P., B.Sc.(Eng.).
Knowles, Henry Lofthouse.
Lister, Harold.
Lodge, Matthew Gordon.
Mahmud, Abdalla Ali, B.Sc.
Meakin, Richard Spurrier.
Moss, Eric, B.Sc.
North, Frederick William, B.Sc.
Perrigo, Albert Edward B.
Phillips, Clive Joseph, B.Sc.
Plews, Harold Heaton, B.Sc.
Pryor, Frederick John.
Sawyer, Wilfrid Albert, B.Sc.(Eng.).
Shaw, Alan Linsley.
Shute, Guy Fleming, B.Sc. (Eng.).
Smith, Charles Cholerton.
Streatfield, Eric Charles.
Tait, Paul John, B.Sc.
Taylor, Robert Roy H., B.Sc.
Ward, Leslie Joseph, B.Sc. Tech.
Webster, Edgar Alan.
Weir, Leonard Francis J., B.Sc.(Eng.).
Welch, Brian Herbert.
Whitaker, Leonard William, B.Sc.(Eng.).
Winckworth, John Wadham.

ACCESSIONS TO THE REFERENCE LIBRARY

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Admiralty, The. Examples in applied mechanics. By authority of the Lords Commissioners of the Admiralty. B.R. 570. 8vo. iv + 204 pp. (London: H.M. Stationery Office, 1938.) 4*s.*

American Institute of Electrical Engineers. A.I.E.E. lightning reference book. Compiled by Lightning and Insulator Subcommittee of the Committee on Power Transmission and Distribution. 4to. 1524 pp. (New York: A.I.E.E., 1937.)

Annett, F. A. Electrical machinery. A practical study course on installation, operation and maintenance. 8vo. xv + 429 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1938.) 18*s.* (*)

Ashworth, J. R., *D.Sc.* Ferromagnetism. The development of a general equation to magnetism. 8vo. xiii + 97 pp. (London: Taylor and Francis, Ltd., 1938.) 7*s.* 6*d.* (*)

Barkhausen, H., *Dr.* Lehrbuch der Elektronen-Röhren und ihr technischen Anwendung. Bd.[e] 3, 4. 8vo. (Leipzig: S. Hirzel, 1935–37.)

Bd. 3, Rückkopplung. xv + 174 pp. *RM.* 7.
Bd. 4, Gleichrichter und Empfänger. *RM.* 9.

Bergmann, L., *Dr.* Ultrasonics and their scientific and technical applications. Transl. by H. S. Hatfield. 8vo. viii + 264 pp. (London: G. Bell and Sons, Ltd., 1938.) 16*s.* (*)

Blakey, R. E., *D.Sc.* The radio and telecommunications engineer's design manual. 8vo. viii + 142 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 15*s.* (*)

Bliss, L. D. Theoretical and practical electrical engineering. 4th ed. 2 vol. ix + 707 pp. (Washington: The Bliss Electrical School, 1931.)

Blume, L. F., *editor.* Transformer engineering. A treatise on the theory, operation and application of transformers. By L. F. Blume, G. Camilli, A. Boyajian, V. M. Montsinger. Edited by L. F. B. 8vo. xiii + 496 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1938.) 25*s.* (*)

Bölte, K., and Küchler, R. Transformatoren mit Stufenregelung unter Last. Theorie, Aufbau, Anwendung. 8vo. 182 pp. (München: R. Oldenbourg, 1938.) *RM.* 9.60.

Böning, P., *Dr.-Ing.* Elektrische Isolierstoffe. Ihr verhalten auf Grund der Ionenadsorption an inneren Grenzflächen. 8vo. vi + 134 pp. (Braunschweig: F. Vieweg und Sohn, 1938.) *RM.* 8.80.

Bowman, F., *M.A.*, *M.Sc.Tech.* Introduction to Bessel functions. 8vo. x + 135 pp. (London: Longmans, Green and Co., 1938.) 10*s.* 6*d.*

Brandenburger, K. Processes and machinery in the plastics industry. Translated by H. I. Lewenz. 8vo. xii + 243 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.). 25*s.*

British Association for the Advancement of Science. Mathematical tables. vol. 6, Bessel functions. pt. 1, Functions of orders zero and unity. Prepared by the Committee for the Calculation of Mathematical Tables. 4to. xx + 288 pp. (Cambridge: University Press, 1937.) 40*s.*

Britten, F. J. The watch and clock makers' handbook, dictionary and guide. 14th ed., revised by J. W. Player. 8vo. vi + 547 pp. (London: E. and F. N. Spon, Ltd., 1938.) 15*s.* (*)

Brown, F. G. W. Higher mathematics for students of engineering and science. 2nd ed. sm. 8vo. xi + 488 pp. (Macmillan and Co., Ltd., 1938.) 10*s.* (*)

Brown, H. A., *M.S.* Radio-frequency electrical measurements. 2nd ed. 8vo. xvi + 384 pp. (New York; London: McGraw-Hill Book Co., Inc., 1938.) 24*s.* (*)

Brown, H. B., and Bryant, A. J. Engineering science. vol. 2, Heat and heat engines and electrotechnics. 8vo. x + 450 pp. (London: Macmillan and Co., Ltd., 1938.) 6*s.* (*)

Buchhold, T., *Dr.-Ing.* Elektrische Kraftwerke und Netze. 8vo. vii + 430 pp. (Berlin: Julius Springer, 1938.) *RM.* 35.

Burnham, T. H. Engineering economics, works organization and management. 4th ed. 2 bks. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) bk. 1, Elements of industrial organization and management. xiii + 288 pp. 8*s.* 6*d.* bk. 2, Works organization and management. x + 330 pp. 8*s.* 6*d.* (*)

Clark, C. H. D., *D.Sc.* The fine structure of matter. pt. 3, The quantum theory and line spectra. (A comprehensive treatise of atomic and molecular structure, vol. 2, pt. 3.) 8vo. pp. lxxii + 459–643. (London: Chapman and Hall, Ltd., 1938.) 15*s.* (*)

Coates, W. A., and Pearce, H., *editors.* The switchgear handbook. vol. 1, Apparatus. [*By various contributors.*] 8vo. vii + 190 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 16*s.* (*)

Cocking, W. T. Wireless servicing manual. 4th ed. sm. 8vo. x + 278 pp. (London: Iliffe and Sons, Ltd., 1938.) 5*s.* (*)

Crowther, J. A., *Sc.D.* Ions, electrons and ionizing radiations. 7th ed. xi + 348 pp. (London: Edward Arnold and Co., 1938.) 12*s.* 6*d.* (*)

Dahl, O. G. C. Electric power circuits: theory and applications. vol. 2, Power system stability. 8vo. xi + 698 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1938.) 42*s.* (*)

Dalzell, J. R., and Hubbard, C. L. Air conditioning, heating and ventilating. 8vo. 571 pp. (Chicago: American Technical Society, 1938.) 16*s.* (*)

Davis, H. T. A course in general mathematics. 8vo. ix + 316 pp. (Bloomington, Indiana: The Principia Press, 1935.) 10*s.* 6*d.*

Electricity Commission. Fire risks at generating stations, etc. Recommendations made by an Investigation Committee appointed by the Electricity Commissioners in respect of stations of major importance, etc. 8vo. v + 15 pp. (London: H.M. Stationery Office, 1938.) 6*d.*

Etherington, H. Modern furnace technology. 8vo. x + 524 pp. (London: Charles Griffin and Co., Ltd., 1938.) 30*s.* (*)

Freytag, H., *Dr.-Ing.* Raumexplosionen durch statische

Elektrizität. 8vo. 115 pp. (Berlin: Verlag Chemie, G.m.b.H., 1938.) *RM.* 3.60.

GOFFIN, P. Stage lighting for amateurs. sm. 8vo. xiii + 178 pp. (London: Frederick Muller, Ltd., 1938.) 5*s.* (*)

GREENLEES, A. E. The amplification and distribution of sound. 8vo. 254 pp. (London: Chapman and Hall, Ltd., 1938.) 10*s.* 6*d.* (*)

GRIFFITHS, W. R. J. The works engineer. A practical manual on building and plant maintenance for the works manager and works engineer. By W. R. J. G. in collaboration with W. O. Skeat. 8vo. viii + 367 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 21*s.*

HAGUE, B., *D.Sc.*, *Ph.D.* Alternating current bridge methods. For the measurement of inductance, capacitance, and effective resistance at low and telephonic frequencies. 4th ed. xvii + 587 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 25*s.* (*)

HARNWELL, G. P. Principles of electricity and electromagnetism. 8vo. xiii + 619 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1938.) 30*s.* (*)

HAVLIK, H. F., *Ph.D.* Service charges in gas and electric rates. 8vo. 234 pp. (New York: Columbia Univ. Press; London: P. S. King and Son, Ltd., 1938.) 12*s.* 4*d.* (*)

HENLEY'S TELEGRAPH WORKS CO., LTD. Practical cable jointing. 3rd ed. sm. 8vo. 341 pp. (London: W. T. Henley's Telegraph Works Co., Ltd., 1938.) 5*s.* (*)

HERBERT, T. E., and PROCTER, W. S. Telephony. A detailed exposition of the telephone system of the British Post Office. vol. 2, Automatic telephony. 8vo. xii + 749 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 20*s.* (*)

HINDMAN. J. A complete system of bookkeeping for electricity supply authorities. 8vo. 136 pp. [London: Gee and Co. (Publishers), Ltd., 1938.] 8*s.* 6*d.* (*)

HOARE, F. E., *Ph.D.*, *M.Sc.* A textbook of thermodynamics. 2nd ed. 8vo. xii + 307 pp. (London: Edward Arnold and Co., 1938.) 15*s.*

HOME OFFICE. A.R.P. memorandum no. C.2. Air raid precautions for electricity undertakings. 2nd ed. 8vo. 33 pp. (London: H.M. Stationery Office, 1938.) 6*d.*

HOUSTON, R. A., *M.A.*, *D.Sc.* A treatise on light. 7th ed. 8vo. xi + 528 pp. (London: Longmans, Green and Co., Ltd., 1938.) 14*s.* (*)

HUTCHINSON, R. W., *M.Sc.* Elementary technical electricity. 8vo. viii + 392 pp. (London: University Tutorial Press Ltd., 1938.) 5*s.* 6*d.* (*)

IBBETSON, W. S. Accumulator charging, maintenance and repair. 6th ed. sm. 8vo. xi + 165 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 4*s.* 6*d.* (*)

INTERNATIONAL ELECTROTECHNICAL COMMISSION. Publications no. 38, 50, 57. 4to. (London, I.E.C., 1938.)

no. 38, I.E.C. standard voltages. 2nd ed. 7 pp. 1*s.*
no. 50, International electrotechnical vocabulary. 311 pp. 10*s.*
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INSTITUTION OF CIVIL ENGINEERS. Regulations for earthing electrical installations to metal water-pipes and water-mains. 8vo. 6 pp. (London: The Institution of Civil Engineers, 1938.) 6*d. post free.*

JAHNKE, E., *Dr.*, and EMDE, F., *Dr.-Ing.* Tables of functions, with formulae and curves. 3rd ed. 8vo. xii + 305 pp. (Leipzig: B. G. Teubner, 1938.) 19*s.*

JONES, H. H. A.C. motors of fractional horse-power. A manual of design, construction and maintenance. sm. 8vo. vii + 189 pp. (London: E. and F. N. Spon, Ltd., 1938.) 7*s.* 6*d.* (*)

JUDGE, A. W. Automobile engine overhaul. sm. 8vo. v + 226 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 4*s.* 6*d.* (*)

KEEN, R. Wireless direction finding. 3rd ed. With a foreword by T. L. Eckersley. 8vo. xi + 803 pp. (London: Iliffe and Sons, Ltd., 1938.) 25*s.* (*)

KERCHNER, R. M., *M.S.*, and CORCORAN, G. F., *M.S.* Alternating-current circuits. 8vo. v + 510 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1938.) 23*s.* 6*d.* (*)

LOEB, L. B. Atomic structure. 8vo. xvi + 446 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1938.) 22*s.* 6*d.*

—— Fundamentals of electricity and magnetism. 2nd ed. xxiv + 554 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1938.) 20*s.*

LYTHALL, R. T. The J. and P. switchgear book; being an outline of modern switchgear practice for the non-specialist user. 3rd ed. 8vo. vii + 431 pp. (London: Johnson and Phillips, Ltd., 1938.) 10*s.* 6*d.* (*)

MACCALL, W. T., *M.Sc.* Electrical engineering. vol. 1. 8vo. viii + 547 pp. (London: University Tutorial Press, Ltd., 1938.) 15*s.* (*)

MITCHELL, H. G., *M.A.* A textbook of electricity. 8vo. xv + 525 pp. (London: Methuen and Co., Ltd., 1938.) 10*s.* (*)

MORLEY, A., *O.B.E.*, *D.Sc.*, and HUGHES, E., *Ph.D.*, *D.Sc.* Mechanical engineering science. A second year course. 8vo. xiv + 260 pp. (London: Longmans, Green and Co., Ltd., 1938.) 4*s.* 6*d.* (*)

OVERTON, L. J. Heating and ventilating. 2nd ed. Edited by F. Herod. 8vo. vi + 287 pp. (Manchester: The Sutherland Publishing Co., Ltd., 1938.) 12*s.* (*)

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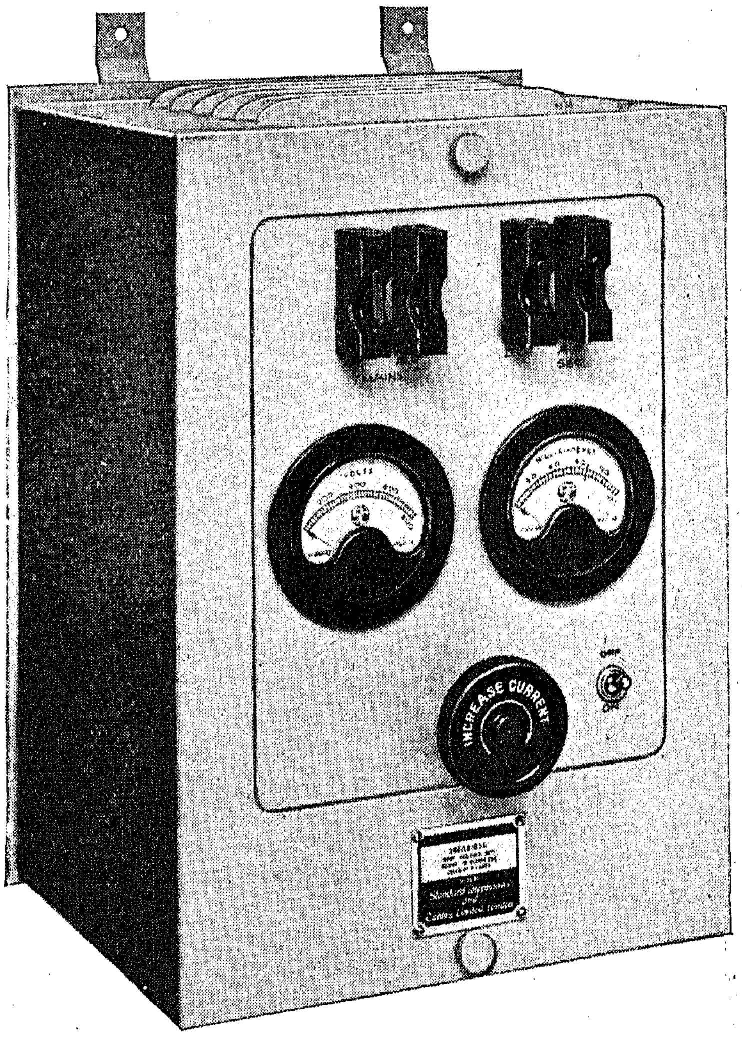

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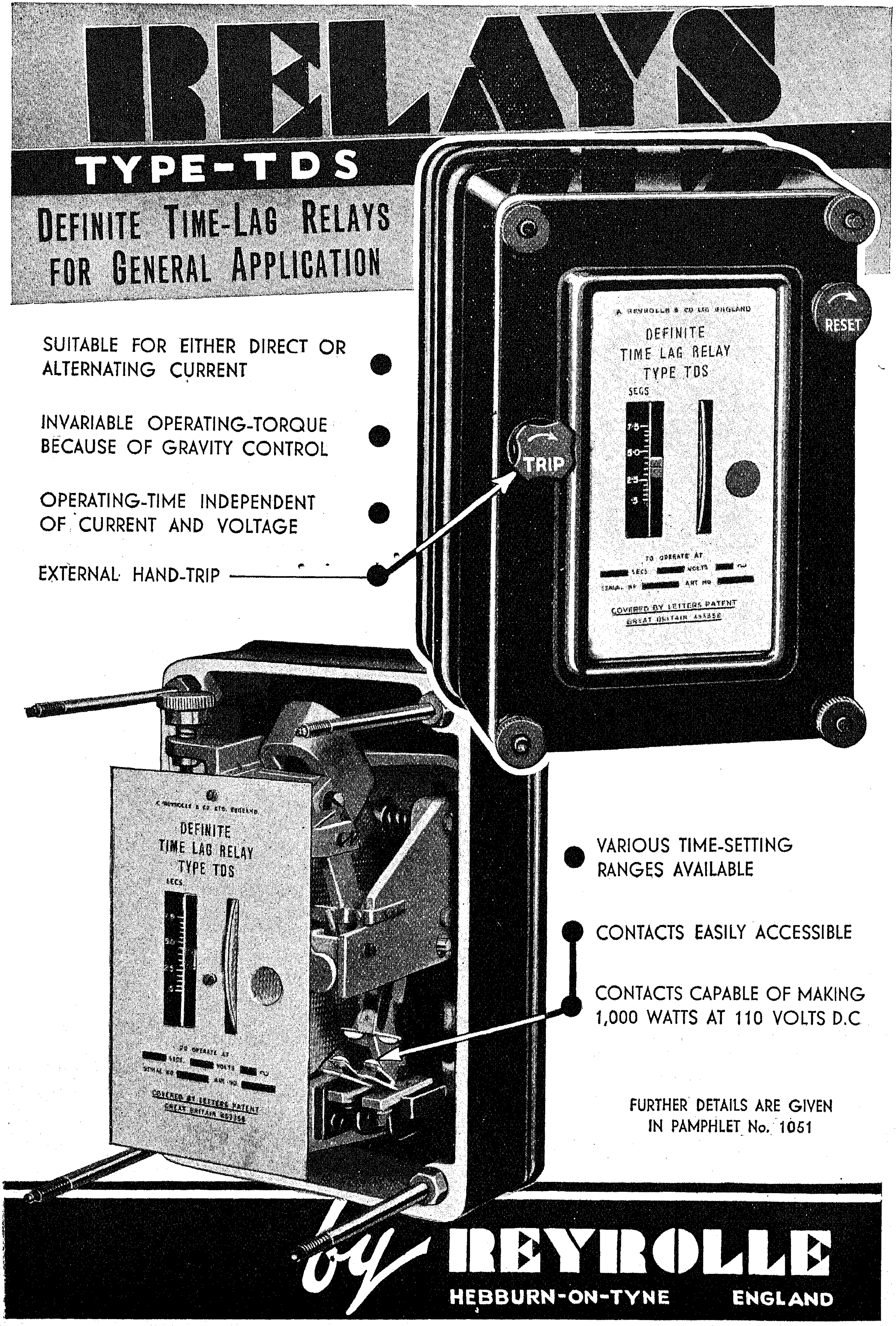

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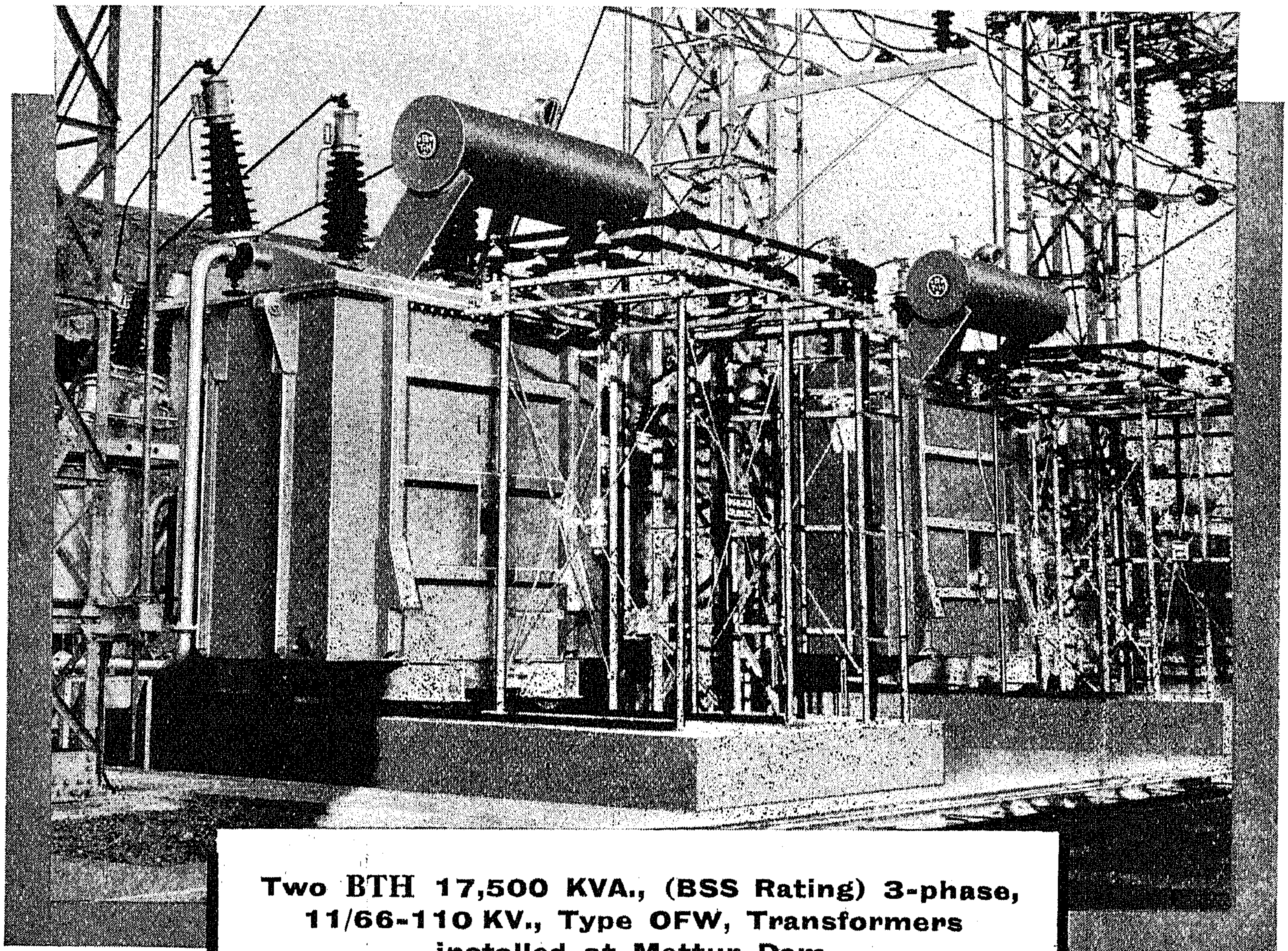

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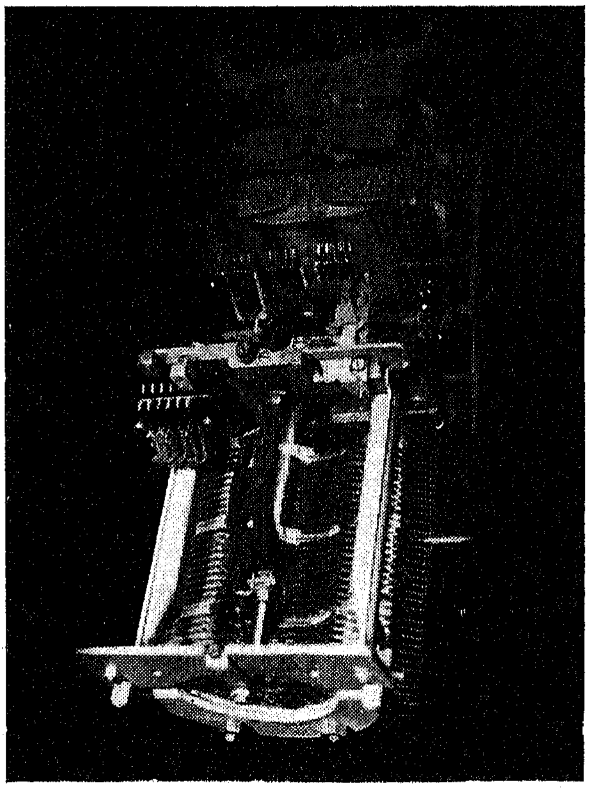

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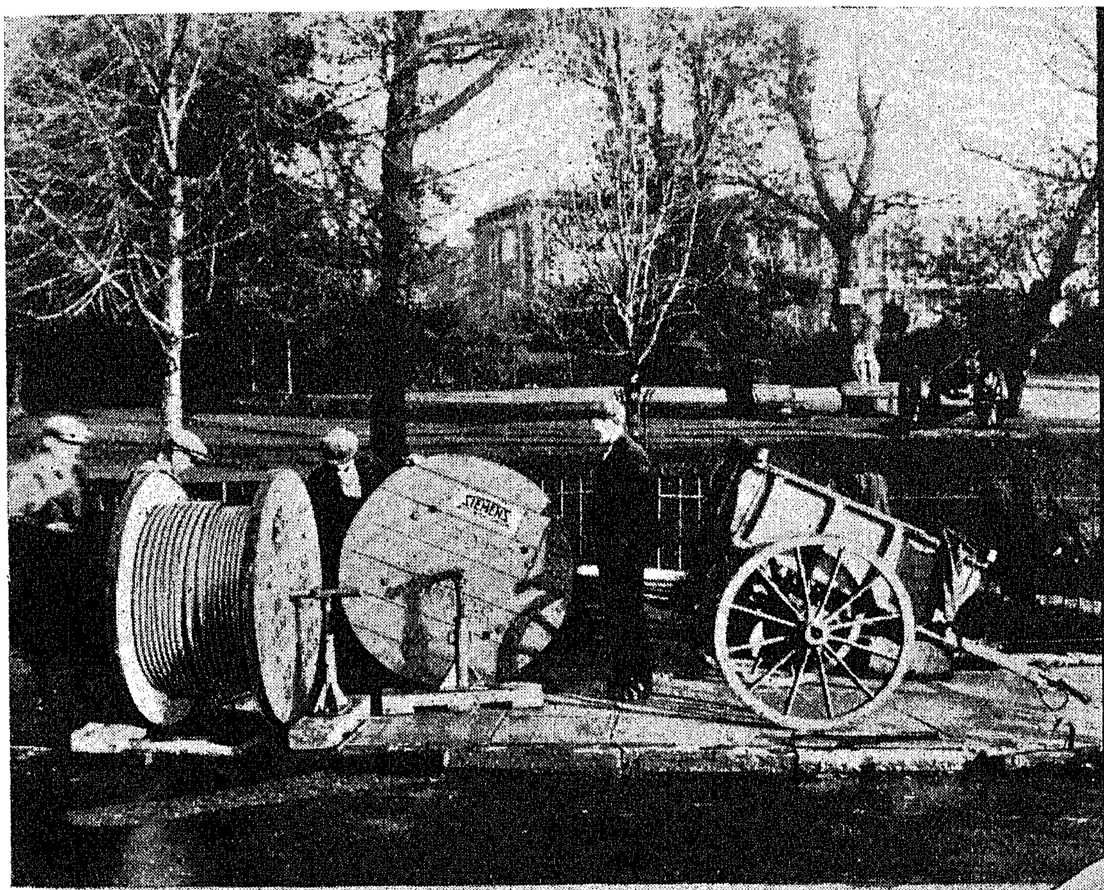

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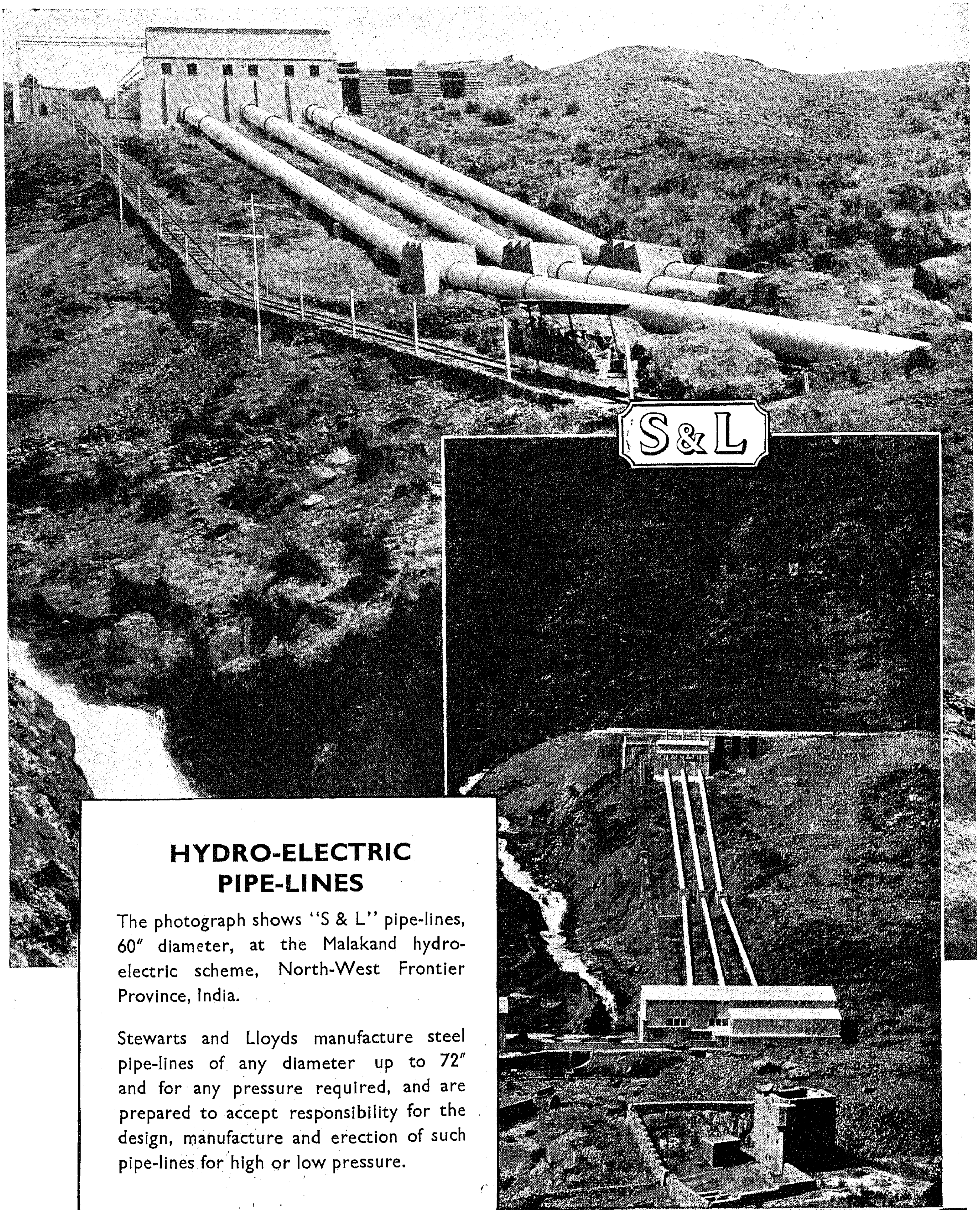

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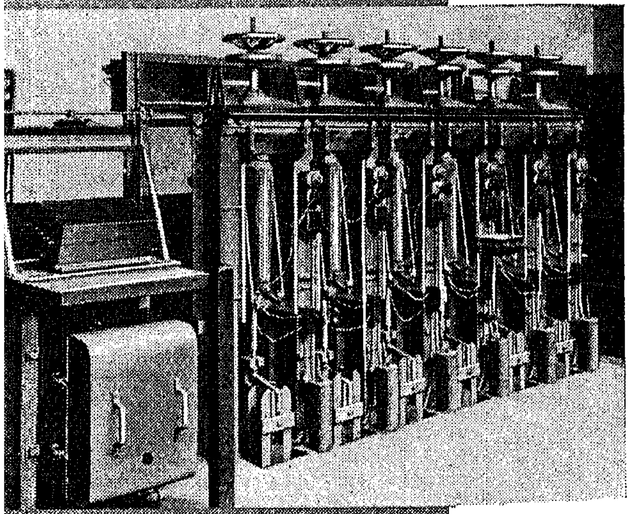

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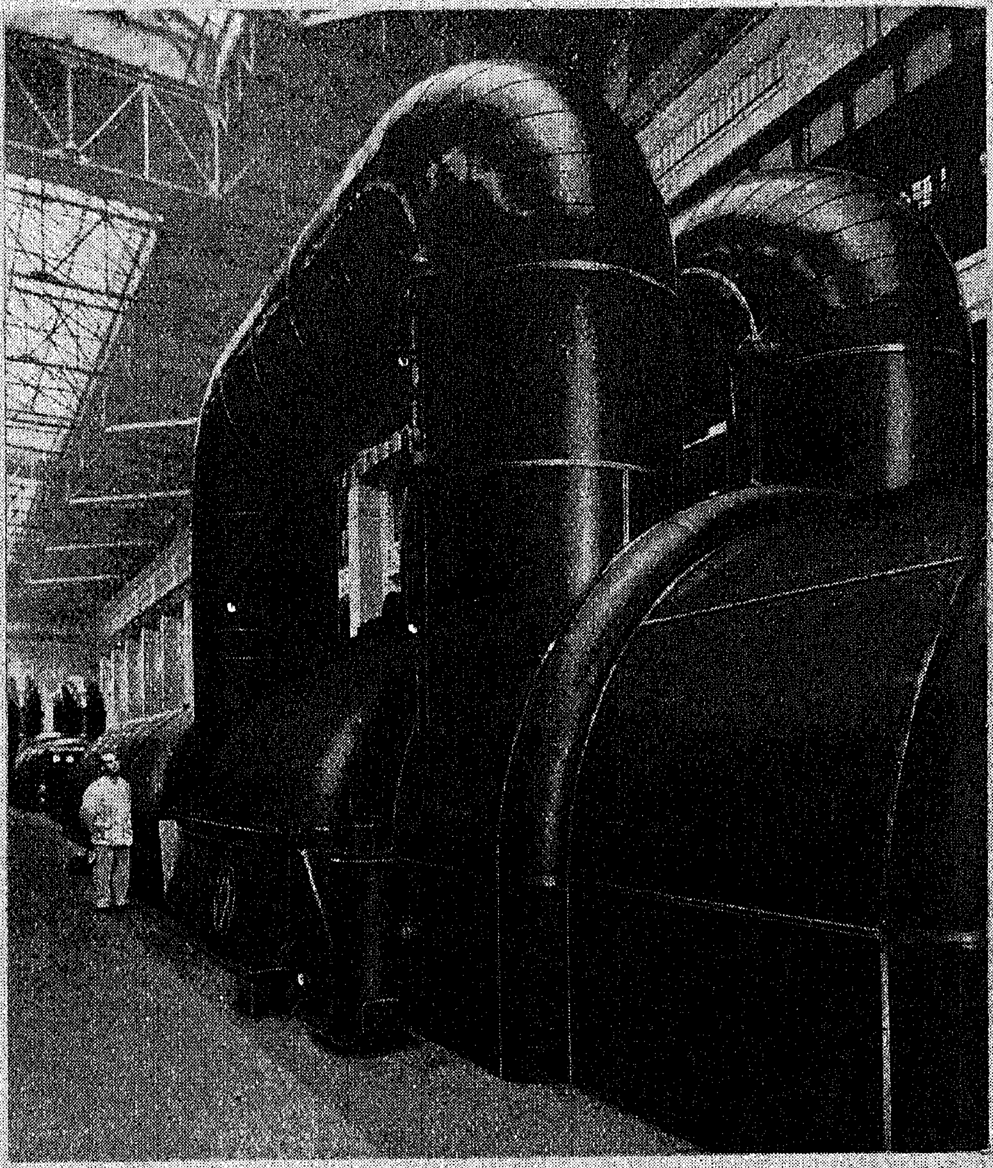

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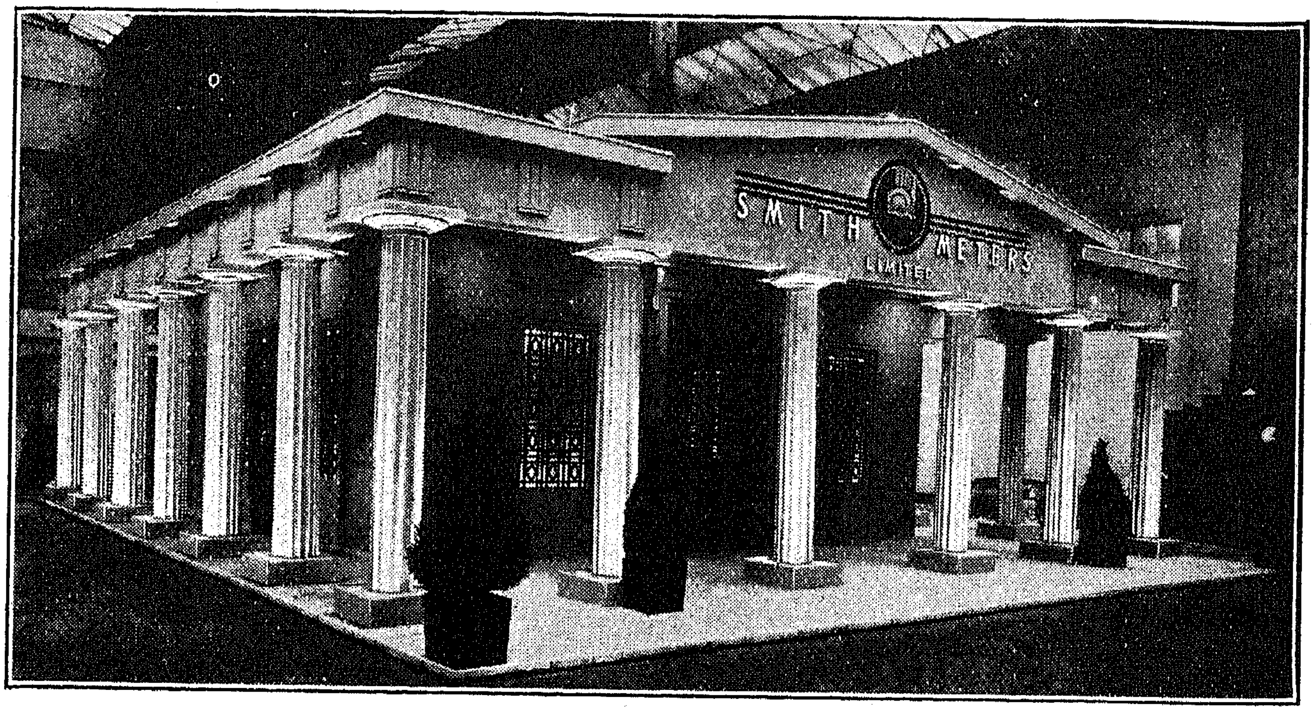

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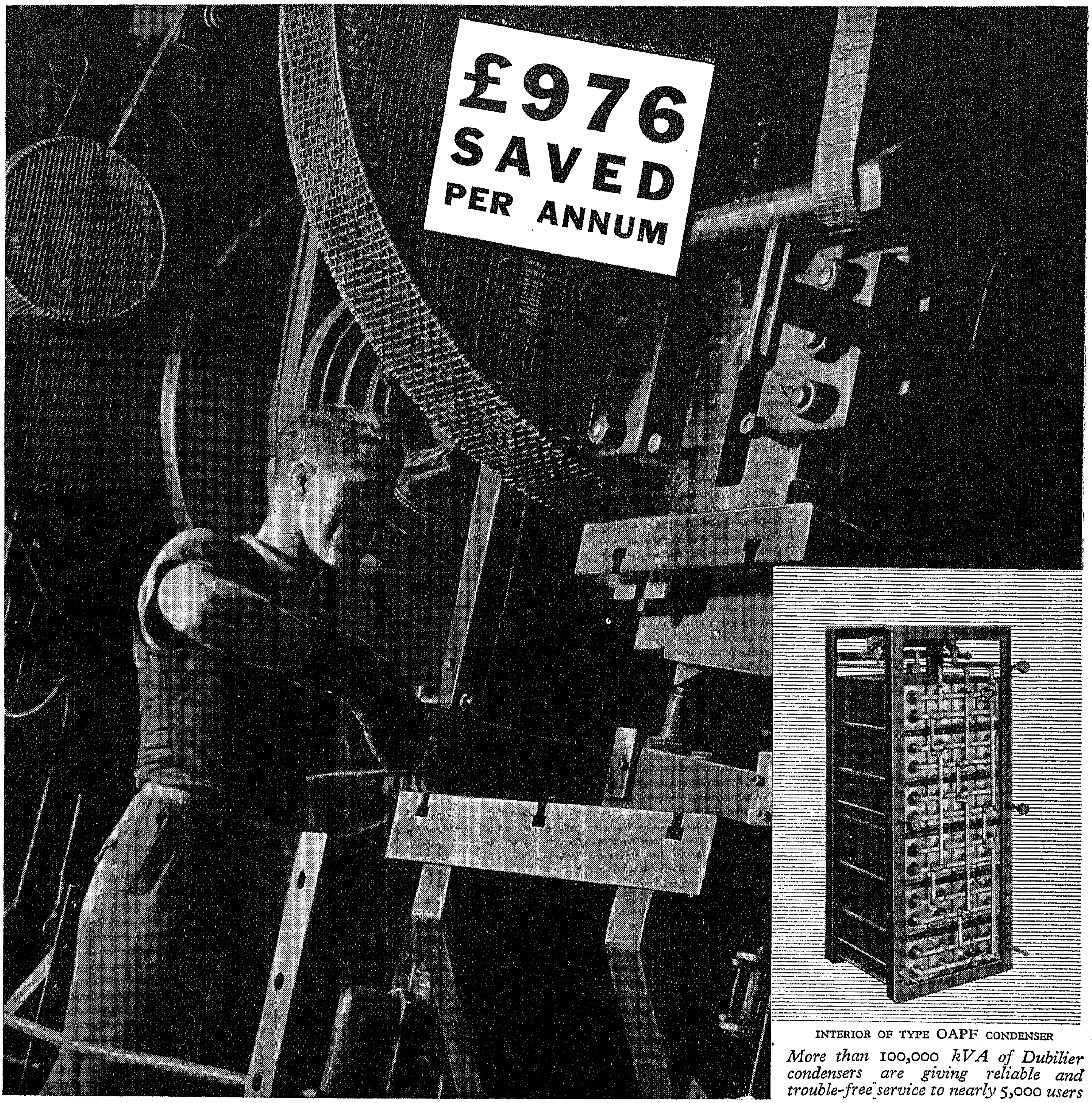

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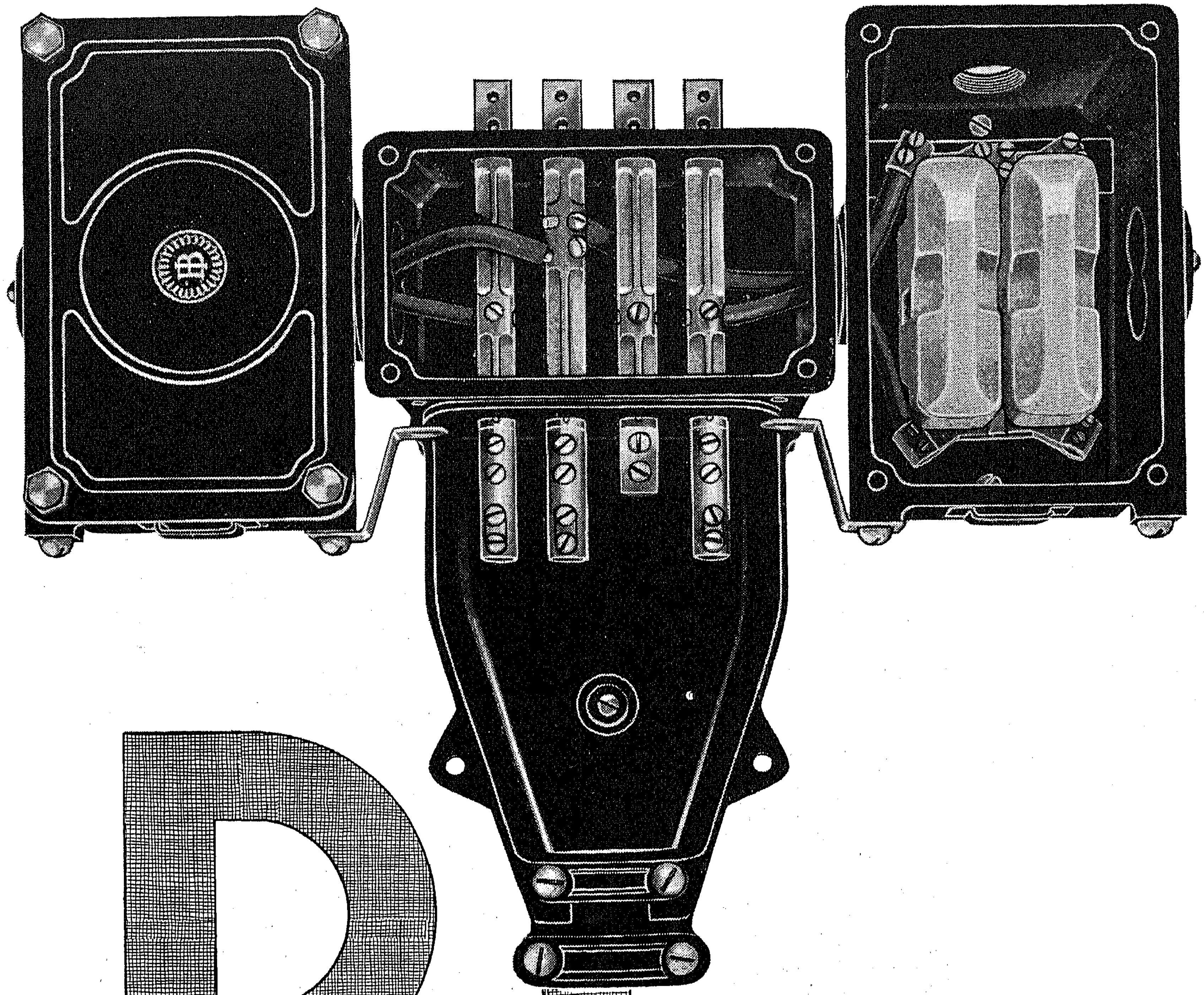

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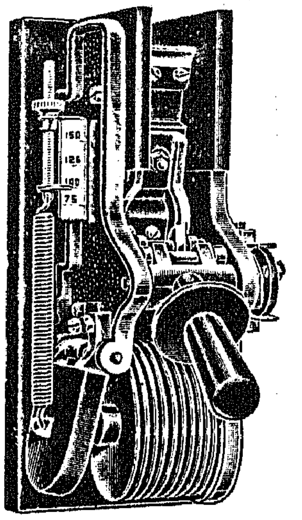

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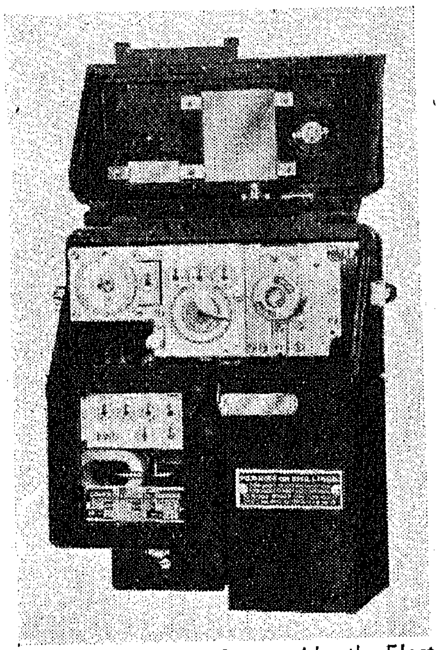

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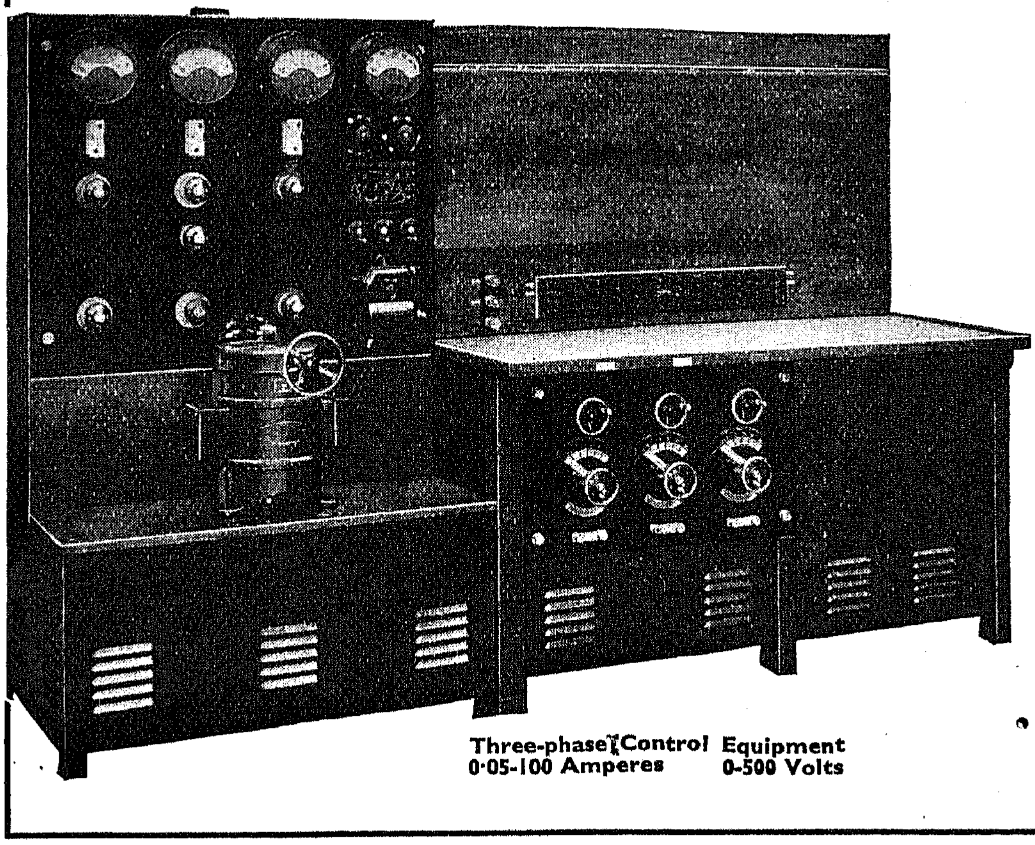

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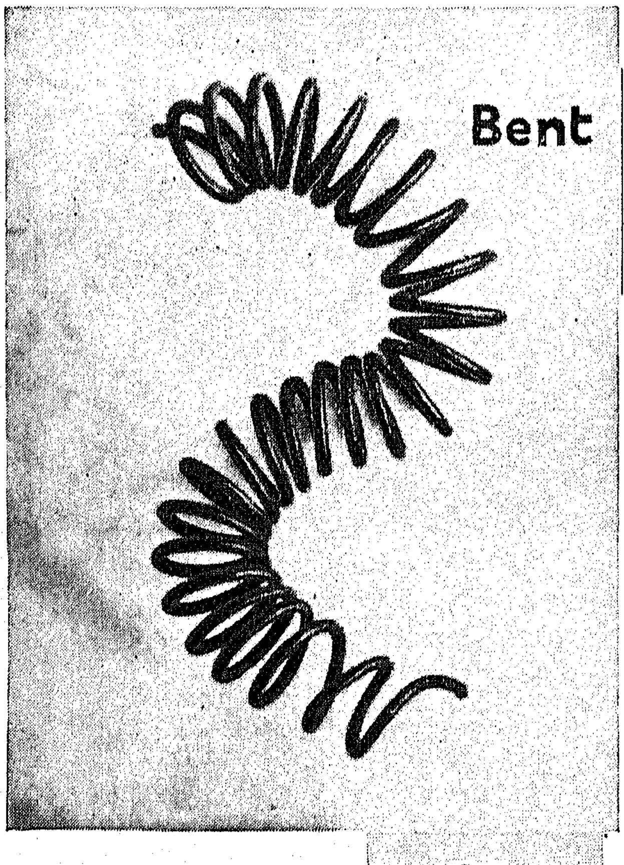

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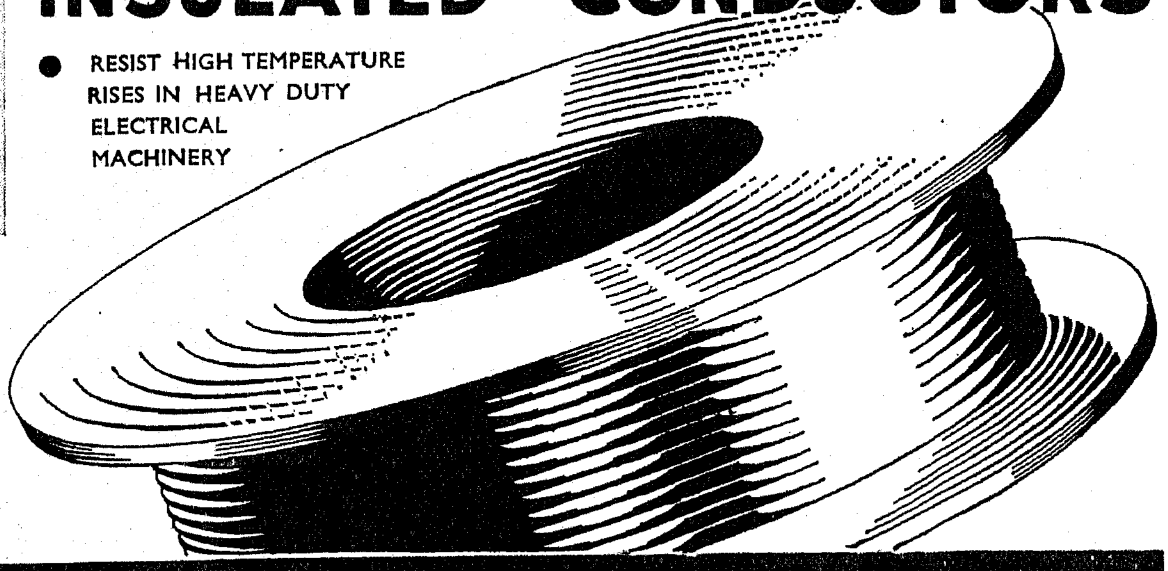

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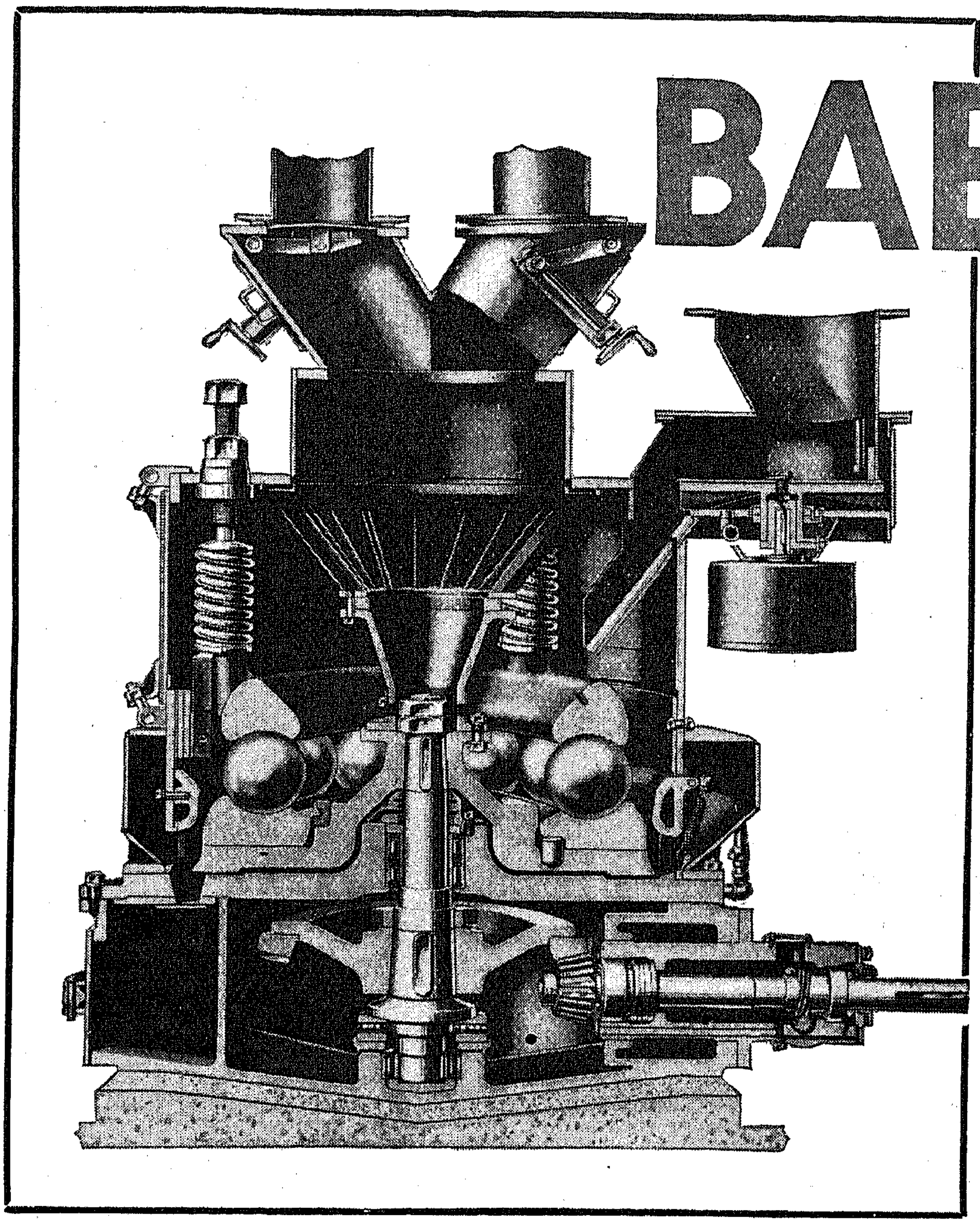

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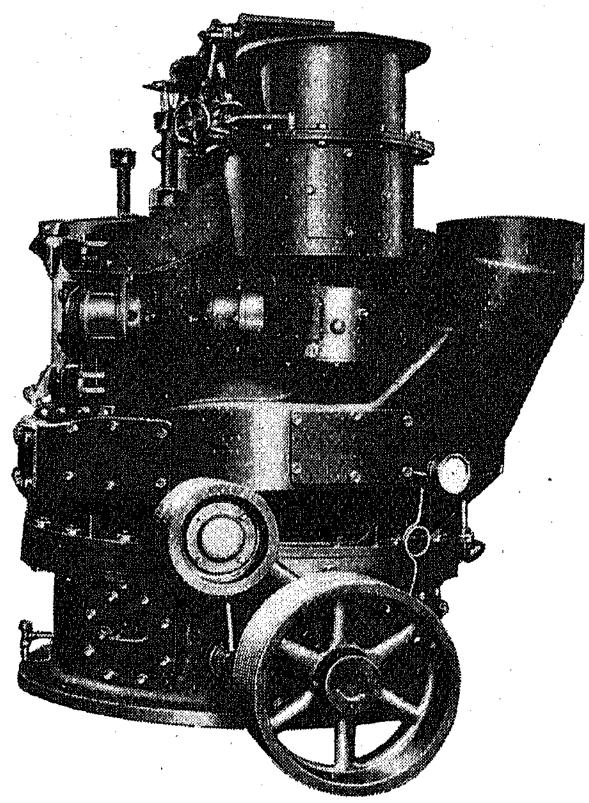

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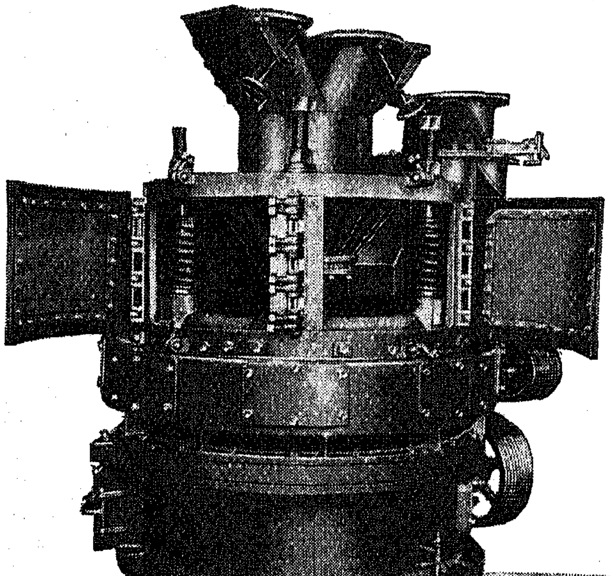

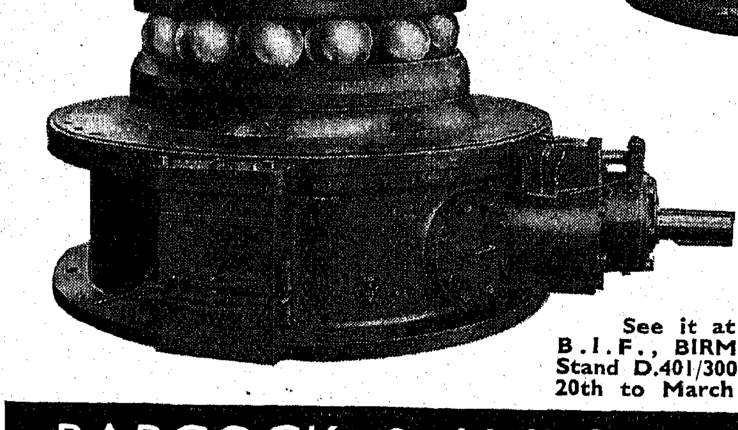

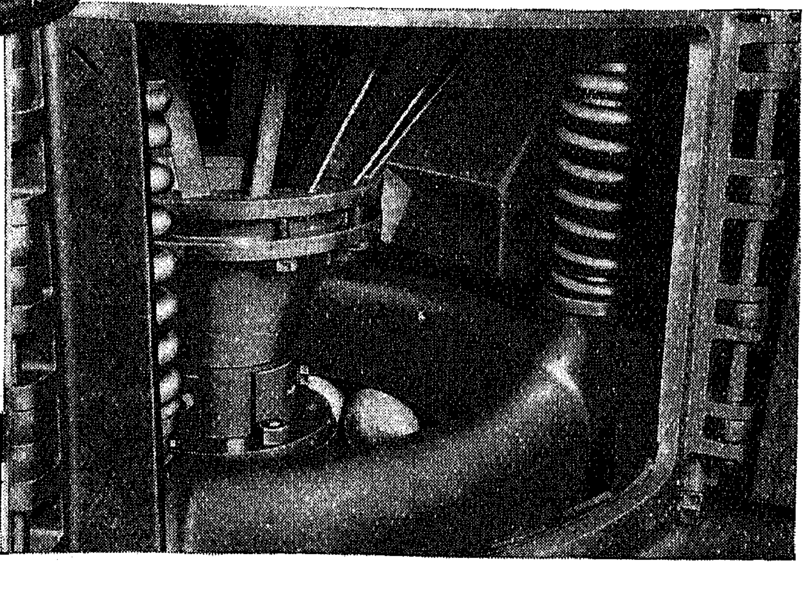

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